High resolution modeling of climate processes in diverse landscapes

NSERC CRSNG

EPCOR

James M. Byrne
Professor and Chair of Geography
University of Lethbridge


Climate Change and Extremes
Workshop
16-17 October *2003, Victoria*, BC

One day record precipitation for Victoria

Science

nature

Science

nature

Social Science

911!!

Graduate Student Cast

- Snow and ice
  - Suzan Lapp; Robert Larson
  - Ryan MacDonald et al
  - Evan Booth
- Soil water, Fire Risk
  - Sarah Dalla Vicenza
- Ecosystem change
  - Ryan MacDonald

Evan Booth

Historical Analysis of

Climate Trends in Western North American

Analysis of Historical Changes in Extreme Temperature and Precipitation in Western North America

Evan J. Booth, James M. Byrne, Ryan J. MacDonald, Stefan W. Kienzle
Water and Environmental Sciences, University of Lethbridge, Alberta, Canada
evan.booth@uleth.ca, byrne@uleth.ca

GC21A-0727

ABSTRACT

Western North America produces a substantial portion of the world food supply. The sustainability of intensive agricultural operations is contingent upon favorable growing conditions and an adequate supply of fresh water. Water resources are coming under increasing pressure from societal demands related in large part to the growing population of Western North America. Global climate change is expected to alter the hydrologic cycle and place additional stress on water supplies and demands. Changing precipitation patterns and intensity, coupled with warming temperatures, could eventually spell disaster for agricultural productivity by increasing the risk of both drought and flooding in sensitive prairie and alpine environments. The goal of this research is to analyze historical climate data to determine the extent to which global warming may have altered the climatology of Western North America over the last 60 years. Daily temperature and precipitation data have been collected from over 1500 stations across Canada and the United States. Climate change indices developed by the WMO's Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI) are applied to evaluate historical change. Trends are calculated using indicators that focus primarily on extremes related to the hydrologic cycle. Station-specific statistical output is then integrated into a GIS to identify spatially coherent trends in temperature and precipitation across Western North America.

METHODS

FORTRAN code was developed to identify and remove stations with substantial missing data. Following the procedure of Frich et al. (2001), annual records were considered to be missing if more than 10% of daily values were missing, or if more than 3 months contained more than 20% missing days. Stations were excluded that did not have at least 75% of years reporting. The final analysis included 490 USA and Canadian climate stations west of the Mississippi River. Indices were calculated on an annual basis for each station for the period 1950-2005 using our FORTRAN code and the RClimDex software developed in conjunction with the ETCCDMI. Trends were calculated using linear regression; significance levels were determined using a standard T-test. Slopes for each trend were then multiplied by 10 to represent change on a decadal scale. Calculated Trends were integrated in ArcGIS and displayed spatially using Local Polynomial Interpolation. Two spatial interpolations were produced for each climate index:

- A. All station trends included regardless of statistical significance;
- B. Using only stations reporting significance at or above 90% confidence level.

FUTURE DIRECTIONS

Further research will focus on applying hydro-meteorological models to utilize the output from this analysis to determine potential impacts of climate change on the soil-moisture balance in sensitive environments. This research will be submitted for publication in early 2010.

TEMPERATURE INDICES

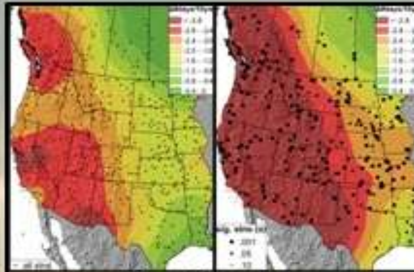


Figure 1: Frost Days

This index measures annual count of days when the daily minimum temperature falls below 0°C. A clear decline in frost days from the Cordillera west suggests substantial historical winter warming.

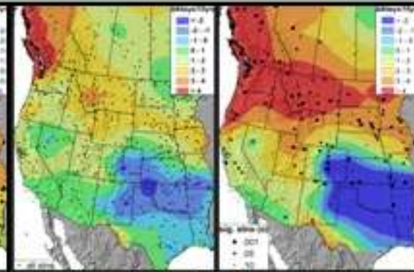


Figure 2: Growing Season Length

This index measures the annual count between the first span of at least 6 days when T>5°C and the first span after July 1 of 6 days when T<5°C. The growing season appears to be increasing in higher latitudes but is shortening slightly in the southeast.

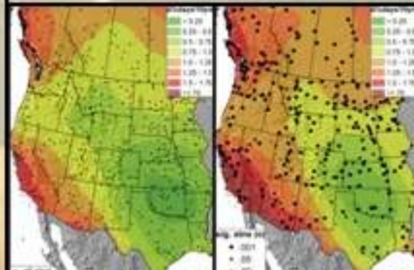


Figure 3: Warm Nights

This index measures the percentage of days in a year when the minimum temperature is greater than the station-specific 90th percentile, calculated from the 1961-90 base period. ALL regional trends indicate warming nighttime temperatures with the greatest increases in the west and north.

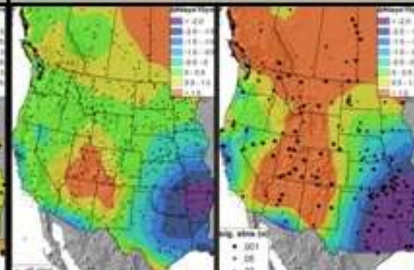


Figure 4: Warm Spell Duration Index

This index measures the greatest annual count of consecutive days when maximum temperature is greater than the station-specific 90th percentile (1961-90 base). The continent interior shows the greatest warming but there is a negative trend over the SE region.

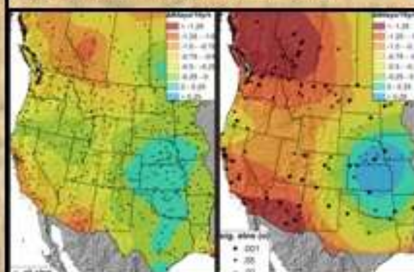


Figure 5: Cold Spell Duration Index

This index measures the greatest annual count of consecutive days when minimum temperature falls below than the station-specific 10th percentile (1961-90 base period). Cold spell occurrence has weakened over the NW quadrant of the study area.

Figure 6: Summer Days

This index measures the annual count of days when maximum temperature is greater than 25°C. Again negative trends are apparent in the SE but trends are positive for the interior regions.

PRECIPITATION INDICES

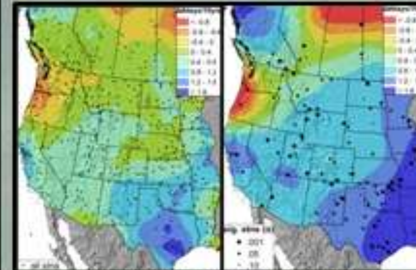


Figure 9: Significantly Wet Days

This index measures the annual count of days with at least 5mm of precipitation. 5mm was deemed to be a meaningful threshold at which precipitation events begin to have an affect on soil moisture content and groundwater recharge.

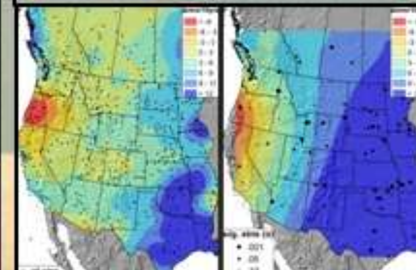


Figure 8: Very Wet Days

This index measures the amount of annual precipitation delivered by daily precipitation events in the station-specific 95th percentile, calculated from the 1961-90 base period. This index represents 'extreme' precipitation events. Extreme events are increasing over the eastern half of the study region.

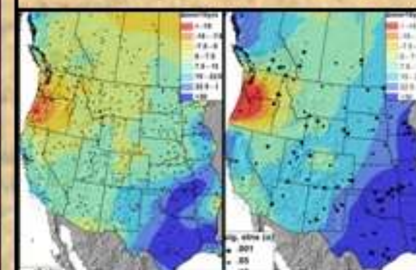
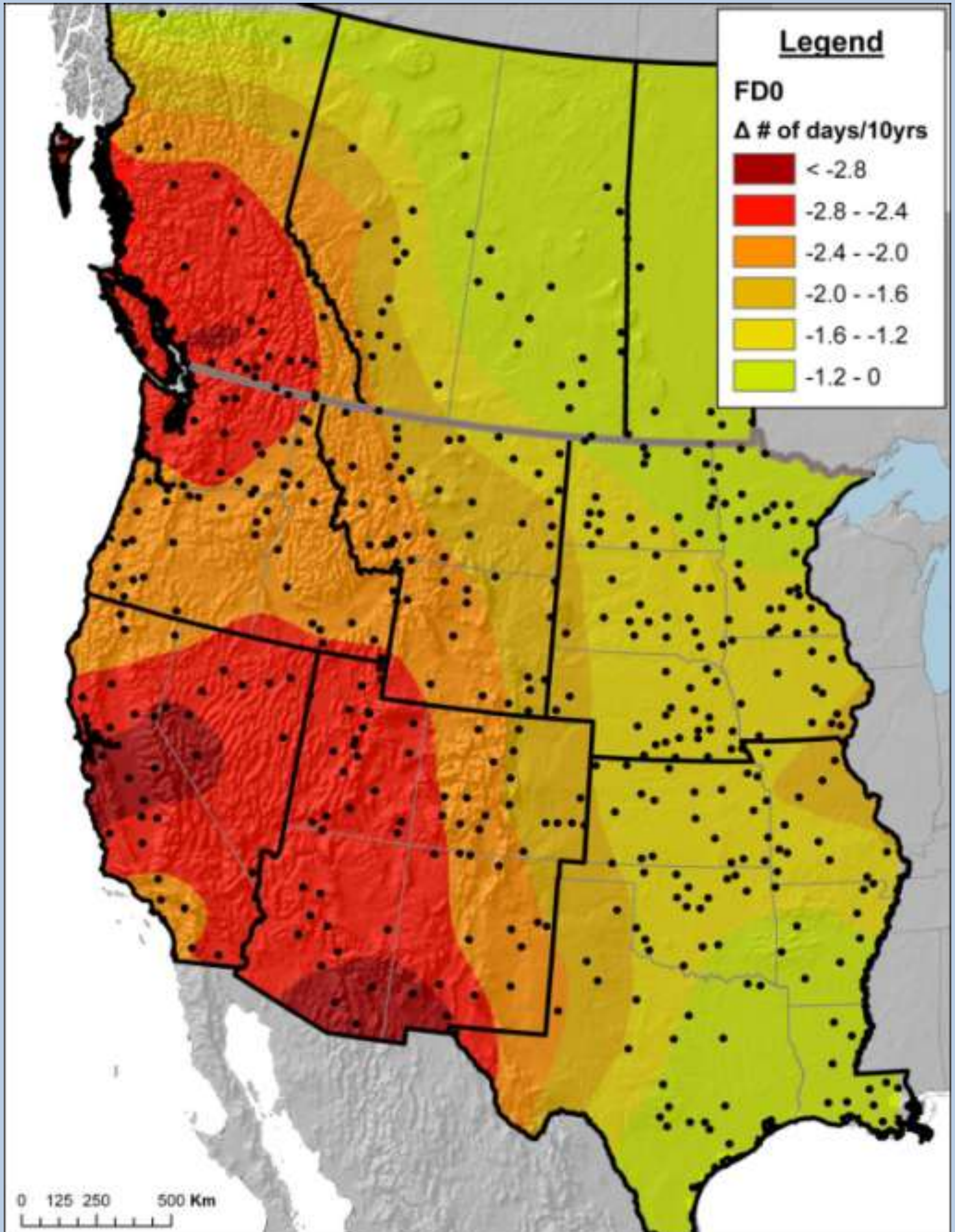


Figure 9: Total Annual Precipitation

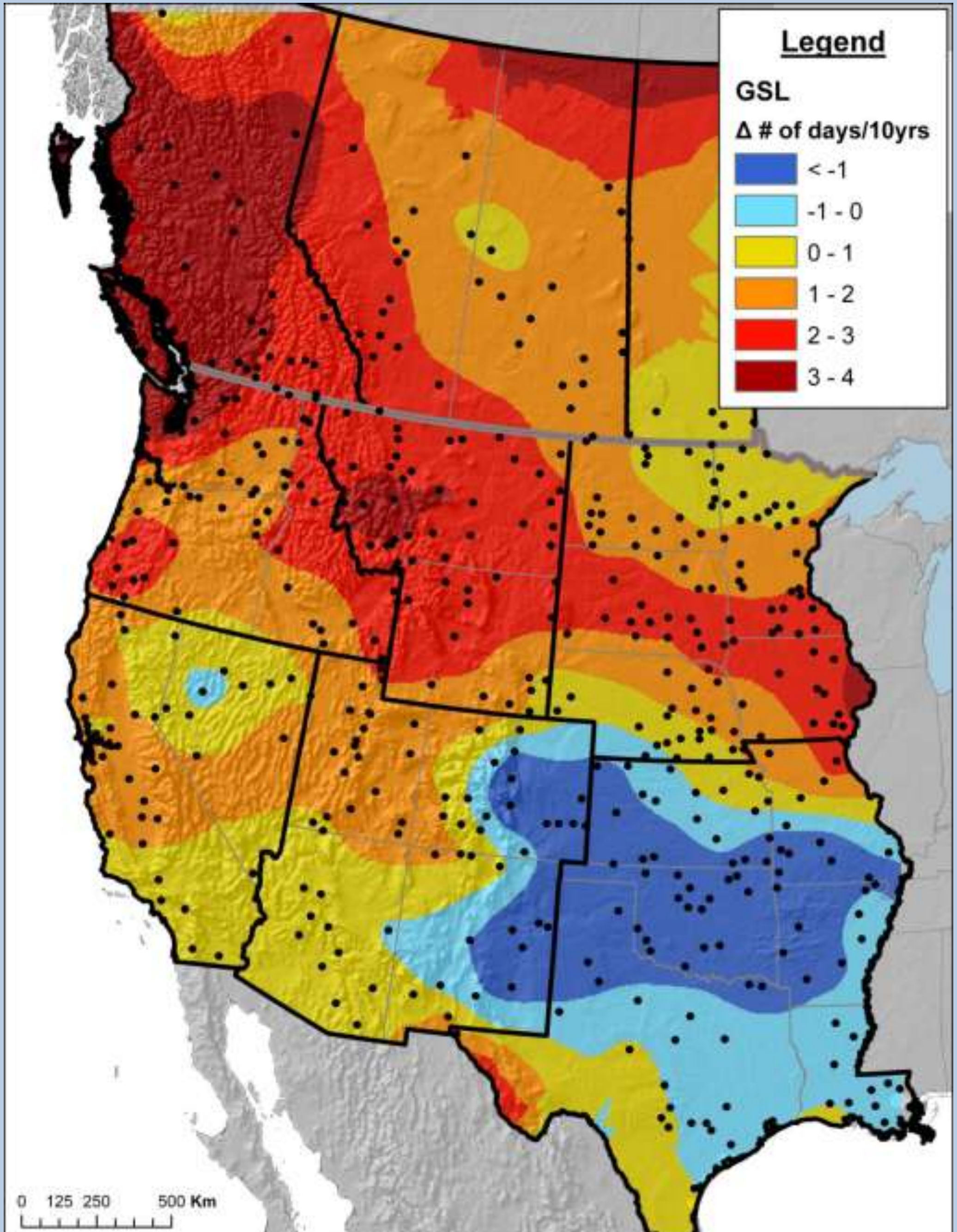
This index measures total annual precipitation received from events greater than 1mm. The spatial pattern echoes the very wet day precipitation, indicating that much of the increase in annual precipitation can be explained by increasingly frequent extreme events in the central part of the continent.



Frost Days (fd0)

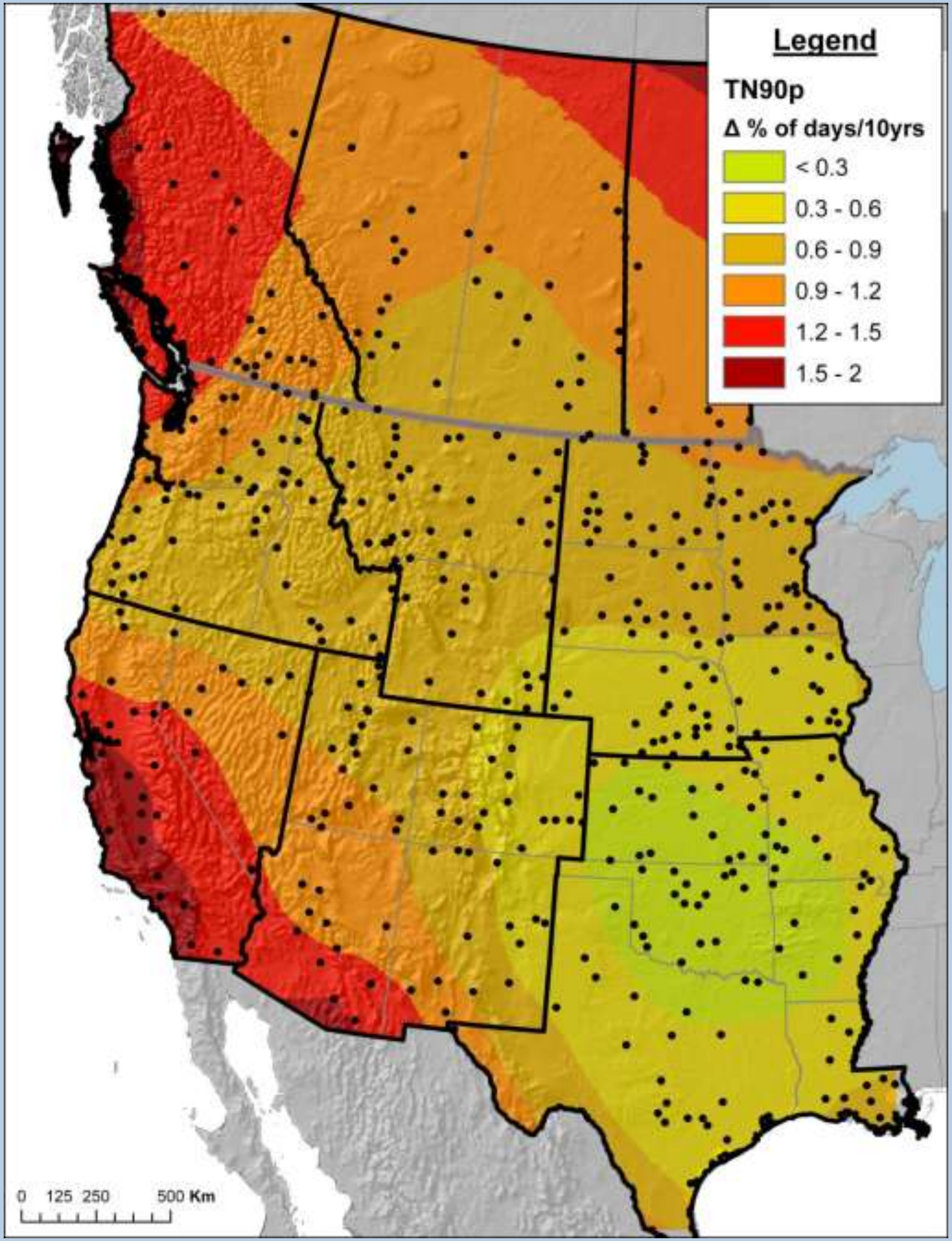
- annual count of days when the minimum temperature is below 0˚C

- Declining FD0 = shortening winter across continent



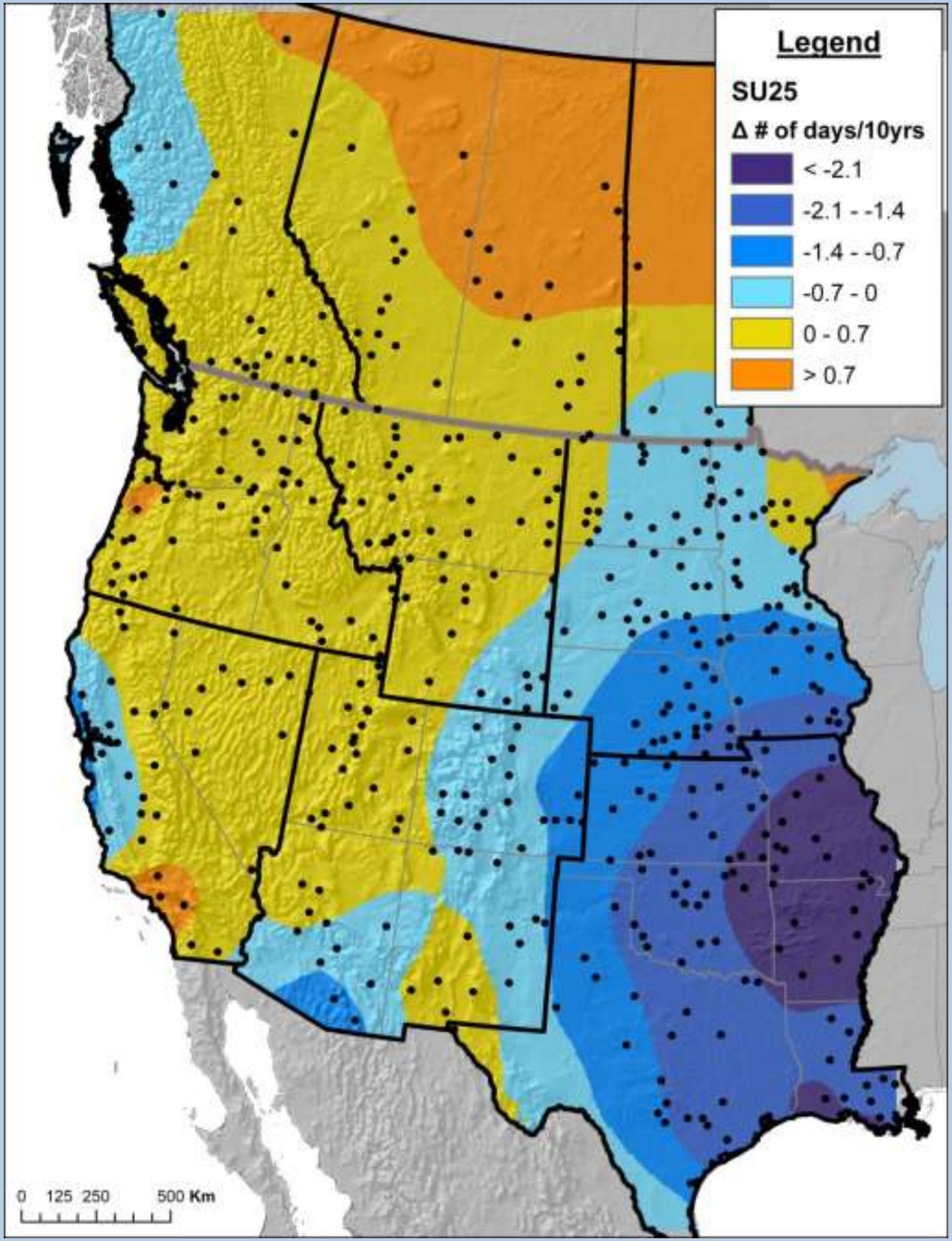
Growing Season Length (gsl)

•Longer growing seasons except one region



Warm Nights (TN90p)

- annual % days
- Tmin > station-specific 90th percentile
- increasing Tmin across continent

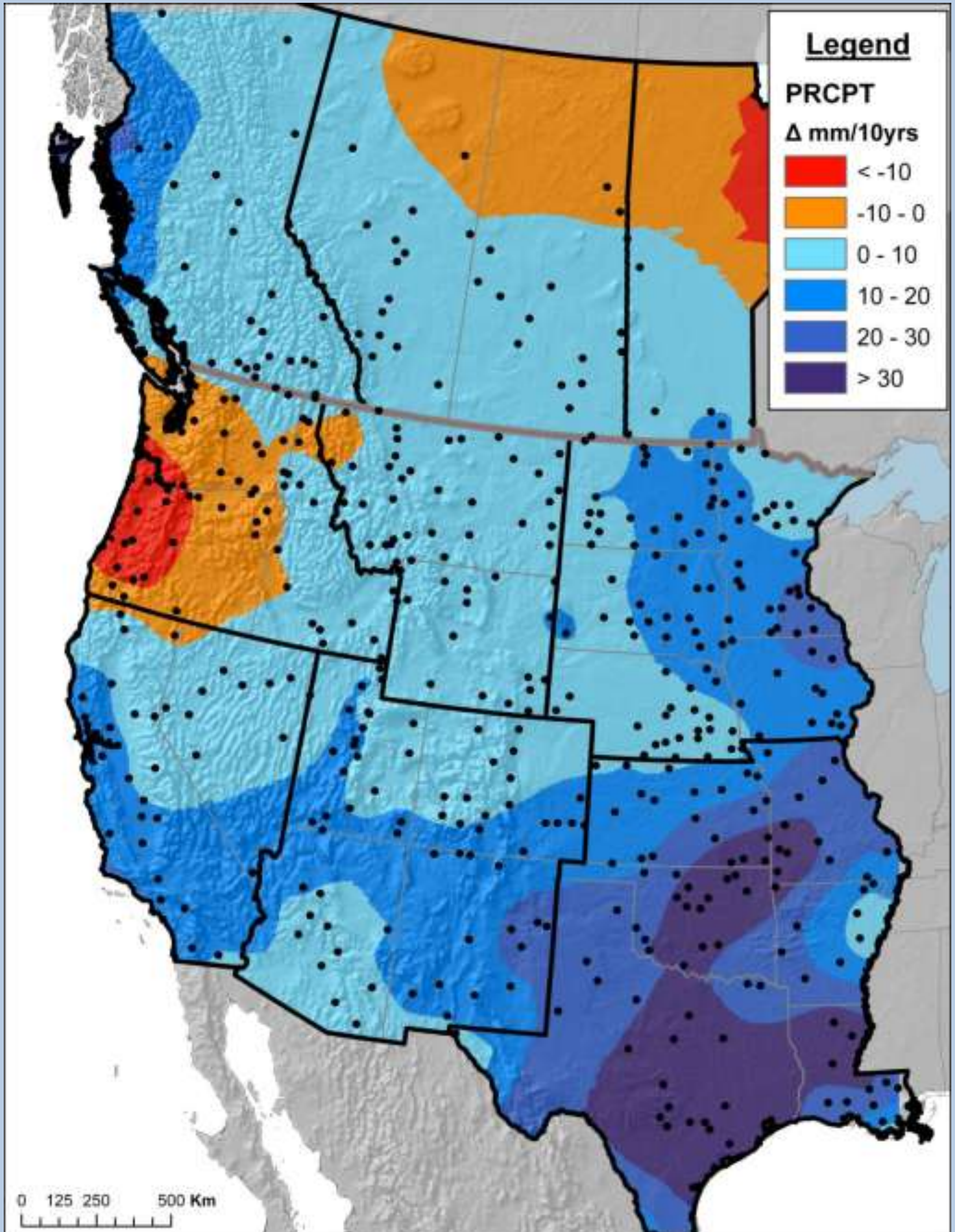


Summer Days (SU25)

- annual count days
- Tmax > 25˚C

- Tmax decline in SE?

- increased cloud/precip

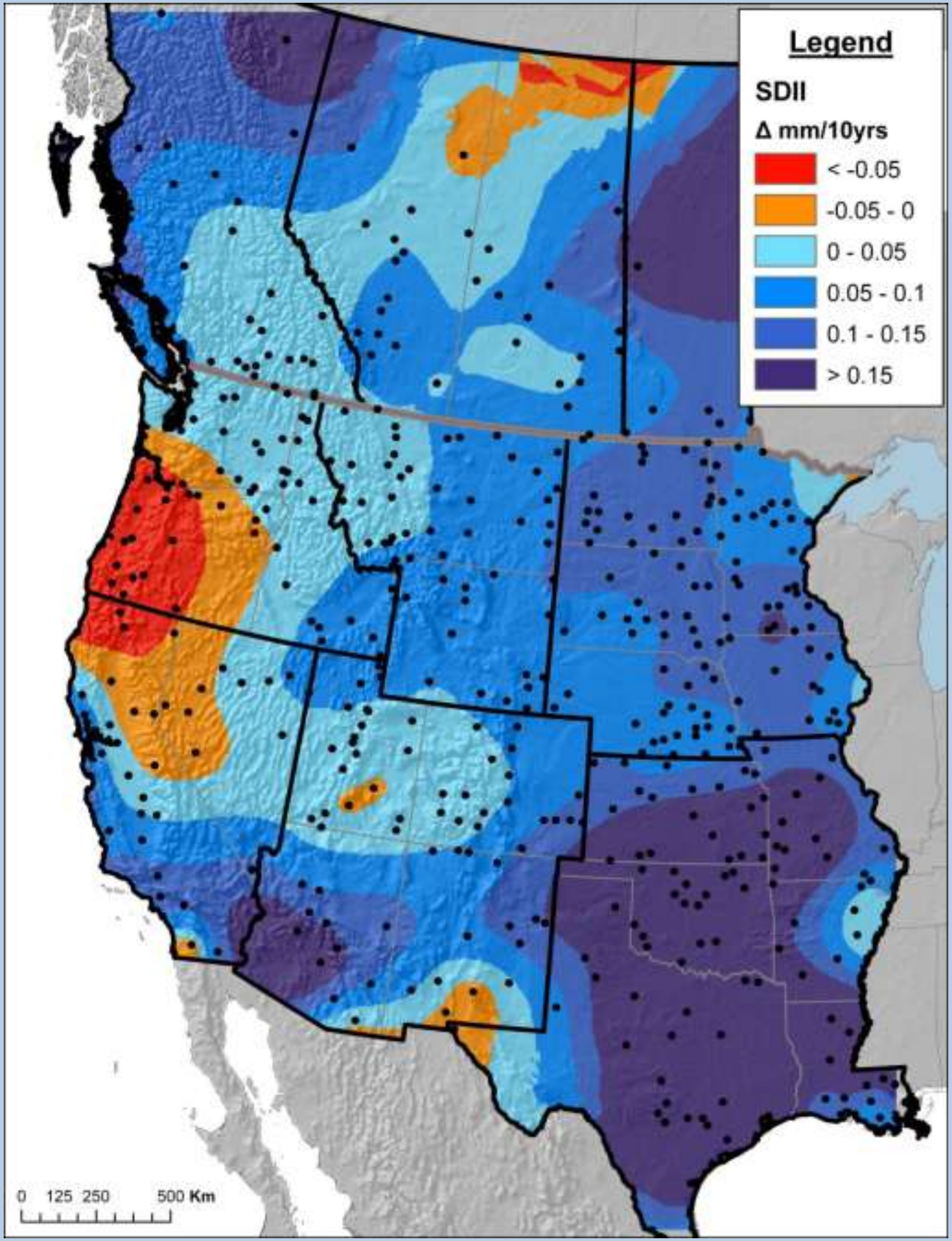


Total Annual Precip (PRCPT)

- annual sum of all recorded precipitation events greater than 1mm

- nearly entire area has seen an increase in precipitation

- Increases are likely offset by rising temperatures and associated PET

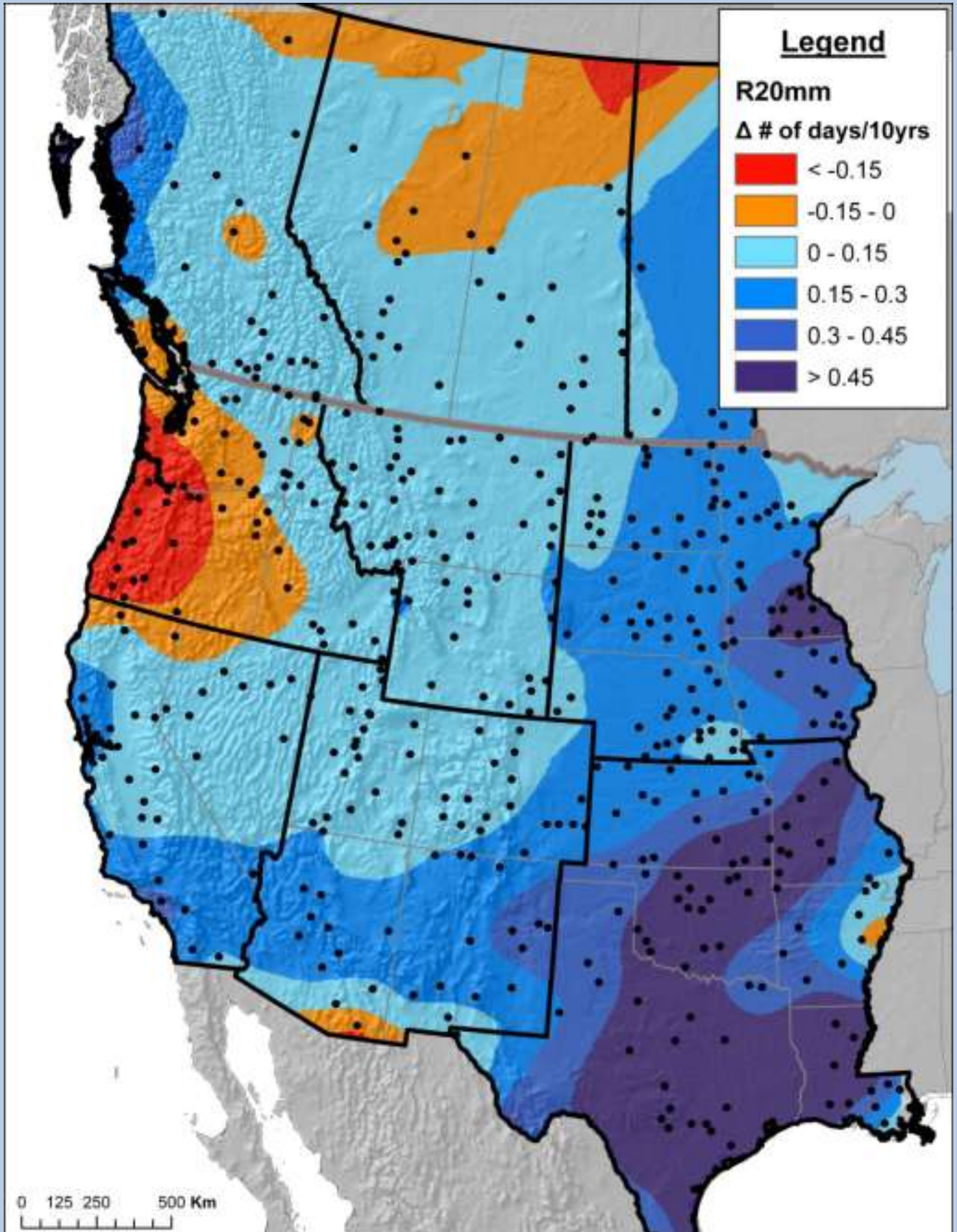


Simple Daily Intensity Index (SDII)

- calculated by dividing the annual number of events by the PRCPT.

- good indicator of whether an intensification of the hydrologic cycle is accompanying temperature changes in western North America

- Eastern half of area has clearly experienced intensification



Very Heavy Precipitation Days (R20mm)

•defined as the annual count of days where precipitation is greater than 20mm

•representing events that can recharge soil water supply

•or potentially cause flooding in some natural environments and urban areas.

GENESYS: 1 ha resolution daily

Terrain Model
- Slope
- Aspect
- Elevation
- Land cover

Micromet
- Temps
- Radiation
- Dewpoint
- Precip
- Wind

Hydromet
- Snowpack
- Glacier ice
- Soil water
- ET, ETP, Sublimation
- Interception

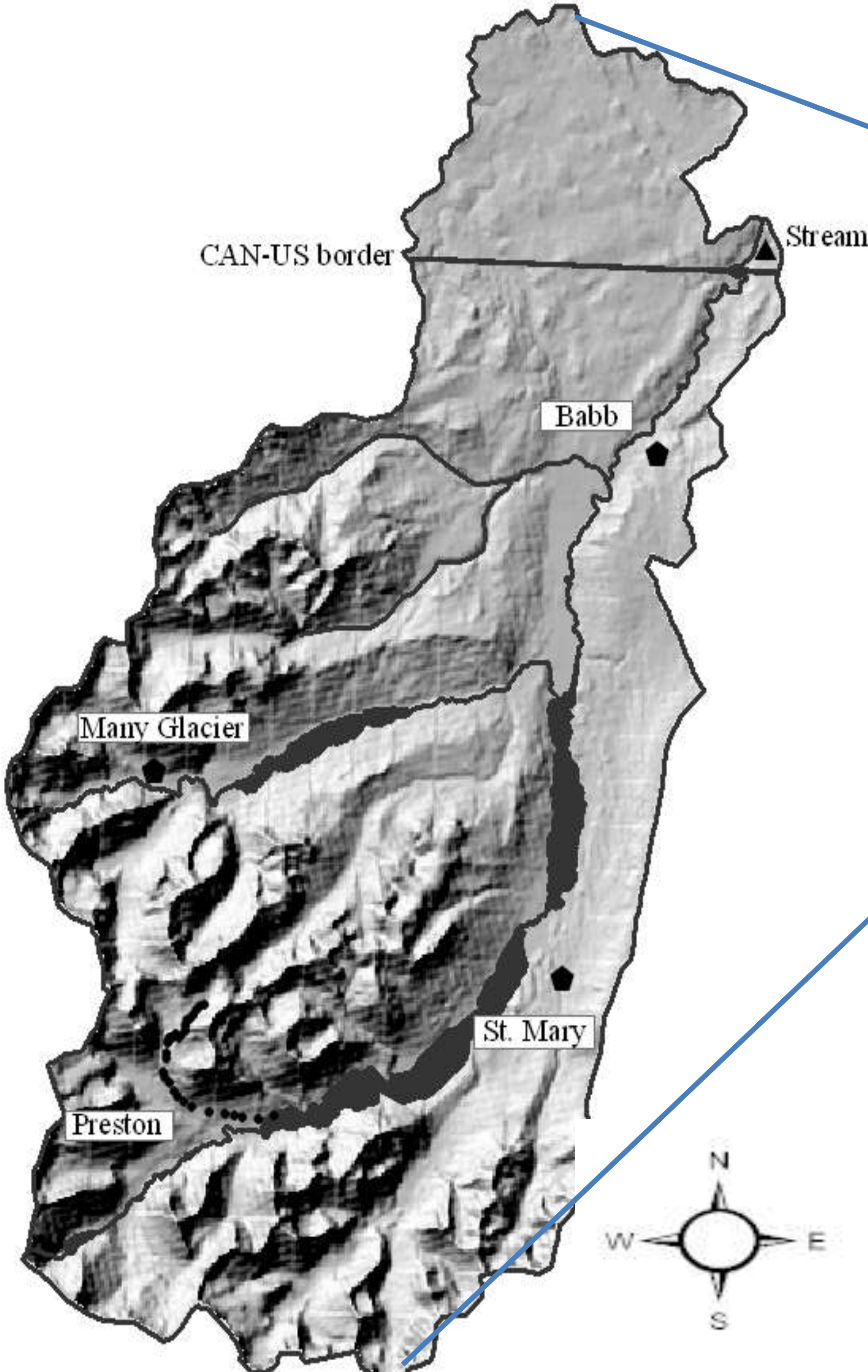
Runoff
Fire risk
Stream temp

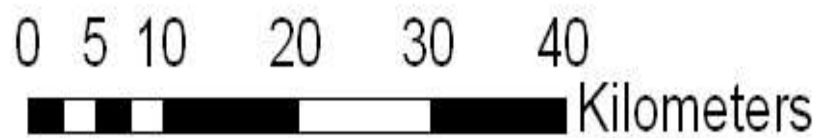
Ryan MacDonald MSc Research

Climate Change Impacts on the St. Mary River, Montana-Alberta

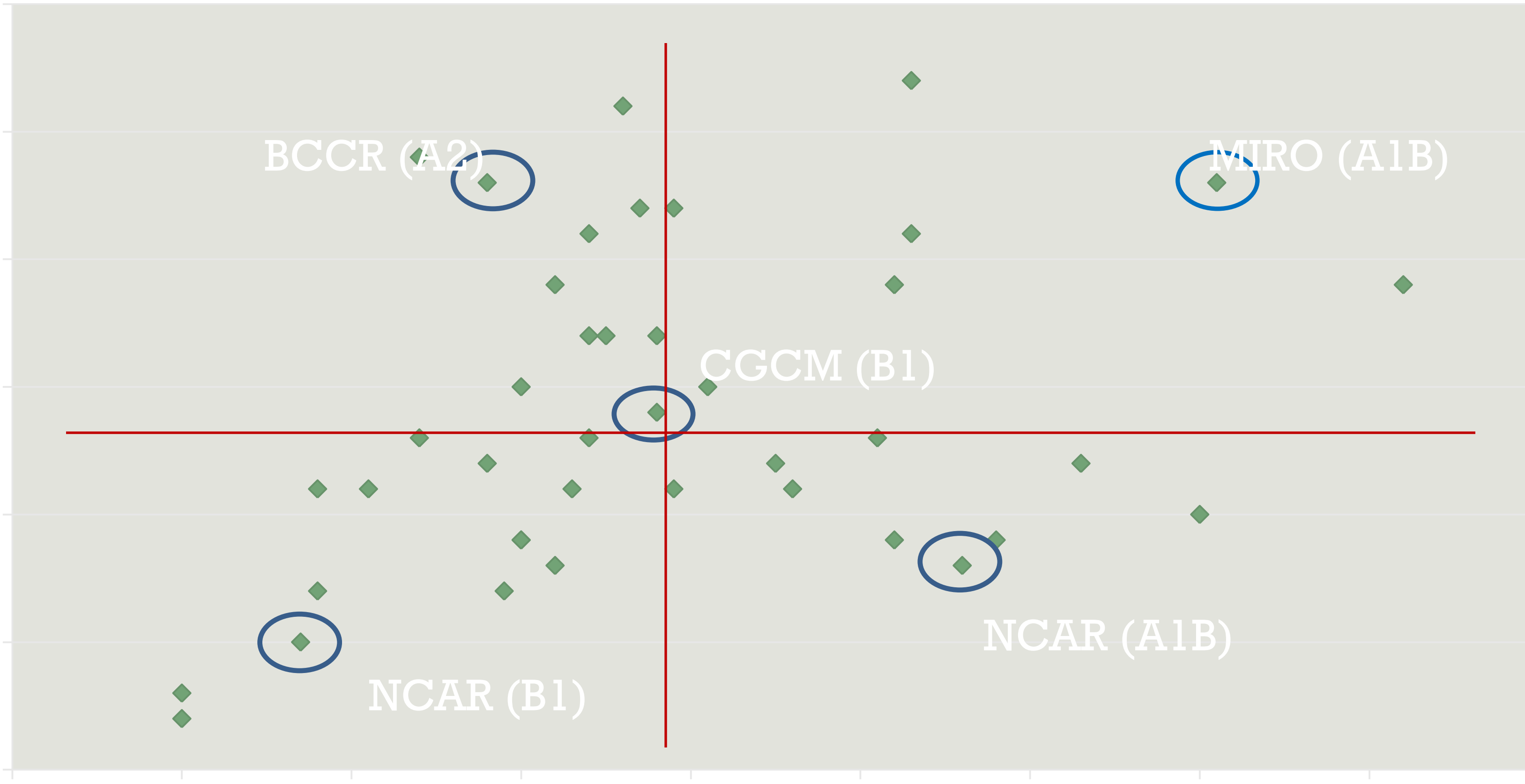
St. Mary Watershed

- 2000 km^2
- Water supply - 300,000 ha irrigation in Canada & USA
- Ecosystem change in Glacier National Park Montana

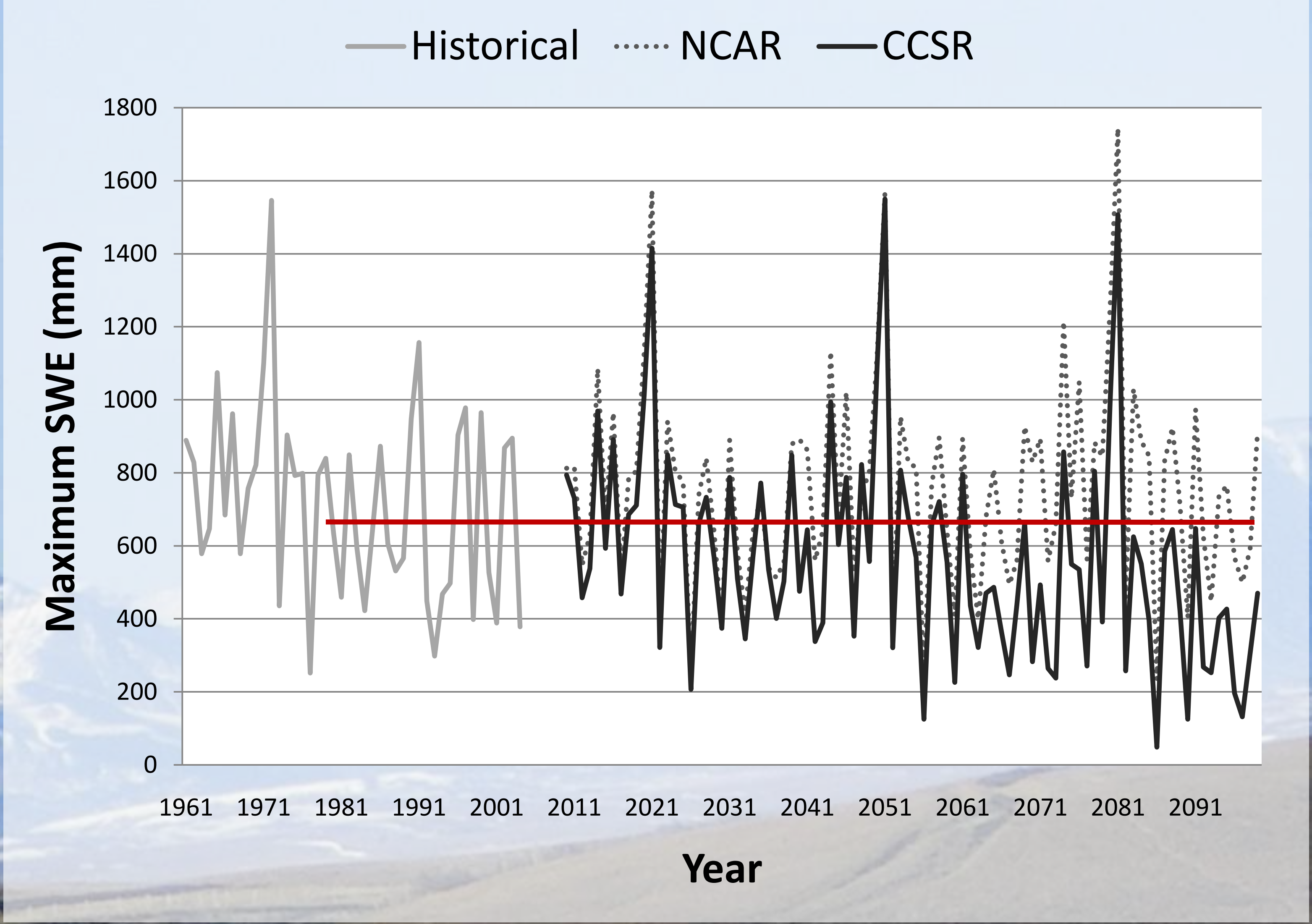




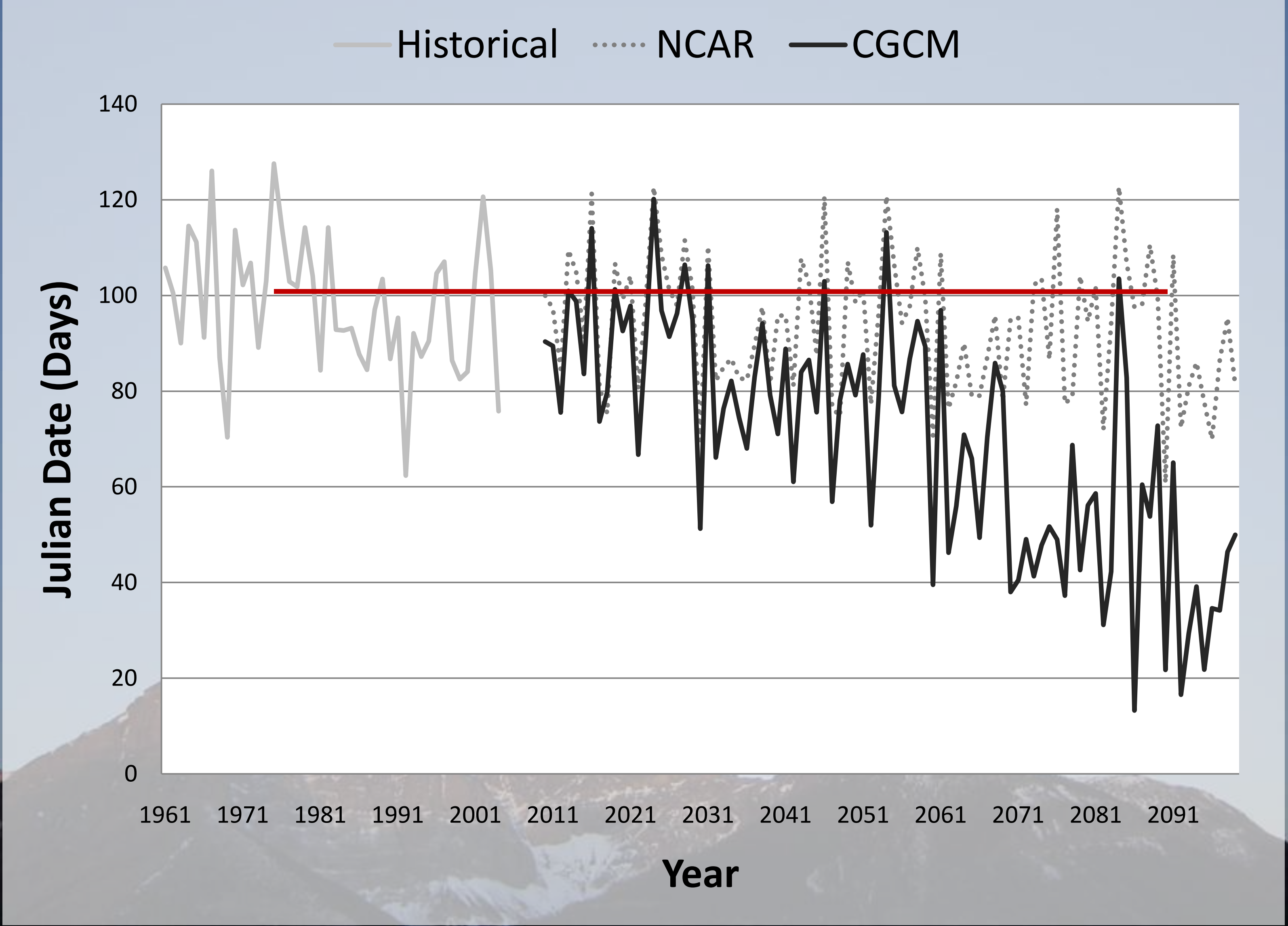
GCM scenario selection 2050s



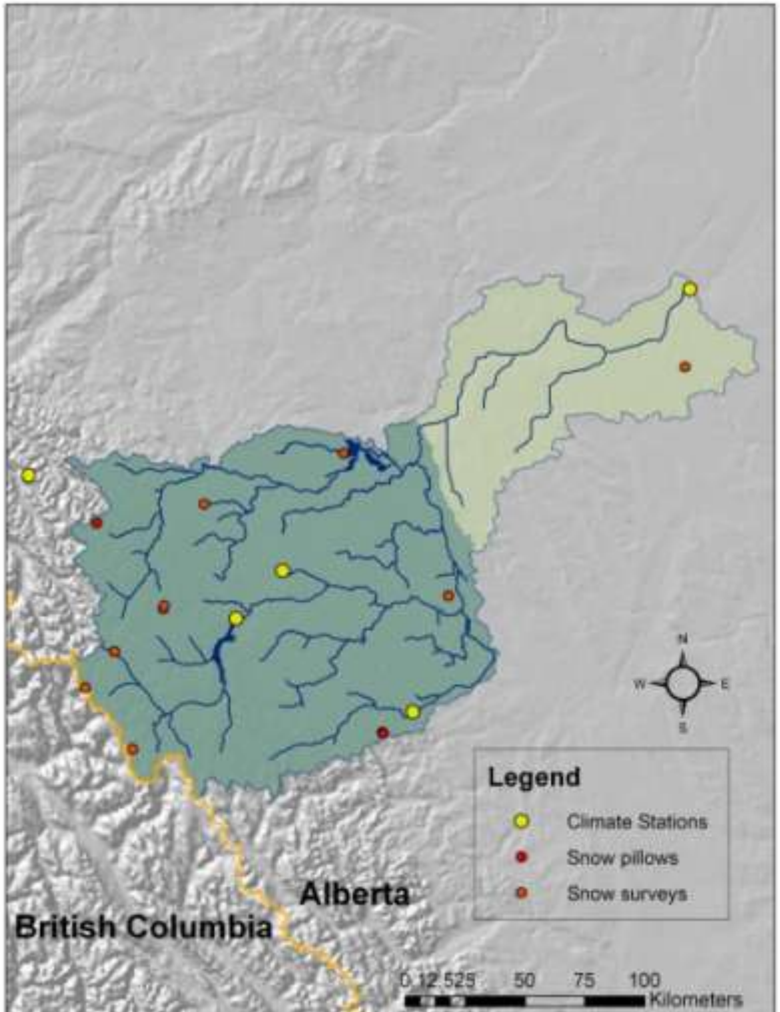
Maximum SWE (mm)



Date of Maximum SWE (Jday)



Upper North Saskatchewan River watershed



- Headwaters 20,527 km^2

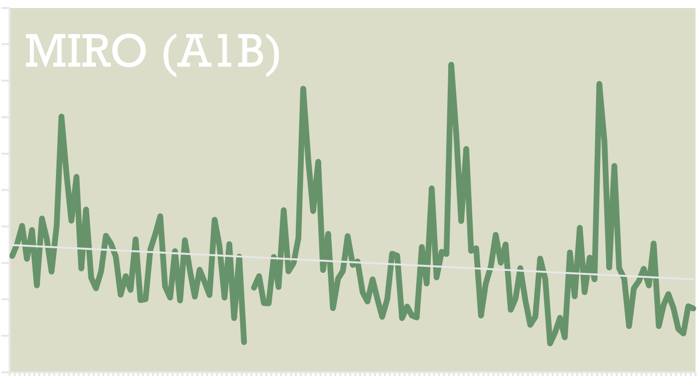
- Elevation range from 752 m to 3484 m

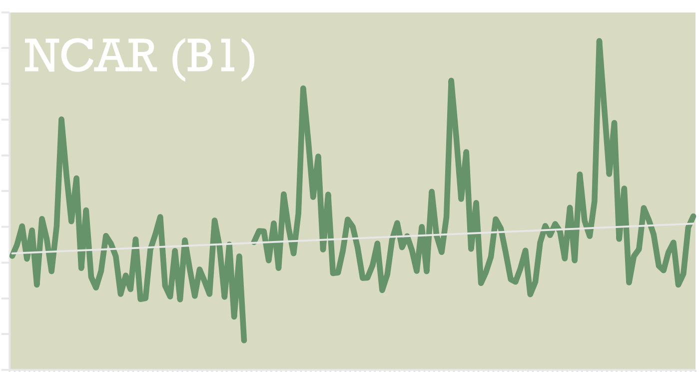
- hydro-electric power, forestry, mineral mining and petrochemical extraction

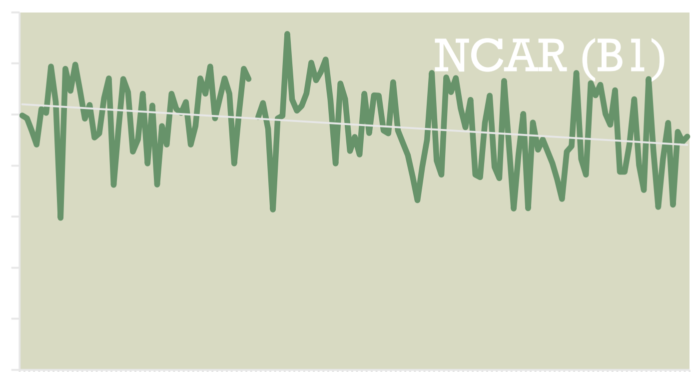
Future SWE predictions

Maximum SWE

Date of maximum SWE







Evan Booth MSc

Modelling the response of Glaciers to Climate Change in the Upper North Saskatchewan River Basin

AGU Fall Meeting 2010

Modeling the Response of Glaciers to Climate Change in the Upper North Saskatchewan River Basin

GC51D-0788

Evan L.J. Booth, James M. Byrne, Hester Jiskoot, Ryan J. MacDonald
Department of Geography , University of Lethbridge, Alberta, Canada
evan.booth@uleth.ca, byrne@uleth.ca

ABSTRACT AND INTRODUCTION

The objective of this M.Sc. research is to quantify historical and potential future impacts of climate change on glacial contribution to streamflow in the Upper North Saskatchewan River (UNSR) basin, Alberta, Canada. The physically-based Generate Earth SYstems Science input (GENESYS) hydro-meteorological model will be used to analyze the regional impacts of historical data, and to forecast future trends in the hydrology and climatology of selected watersheds within the basin. This model has recently been successfully applied to the St. Mary River watershed, Montana, and the UNSR basin (MacDonald et al. 2009; MacDonald et al. *in press*; Byrne et al. *in review*). Hydro-meteorological processes were simulated at high temporal and spatial resolutions over complex terrain, focusing on modeling snow water equivalent (SWE) and the timing of spring melt. A glacier mass balance model is currently in development for incorporation into GENESYS to more accurately gauge the effects of climate change on glaciated areas located in the UNSR basin. General Circulation Model (GCM) scenarios will be applied to develop meaningful projections of the range of future hydrologic change under reduced glacial conditions in the basin through 2100.

STUDY AREA

Figure 1: Study area in regional context.

Figure 2: Study area in detail.

Figure 3: 1961-1990 climate normals for Bighorn Dam.

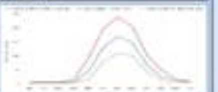


Figure 4: UNSR hydrograph at Whirlpool Point (05DA009).

The UNSR flows northeast from its headwaters on the eastern slopes of the Canadian Rocky Mountains through Edmonton, Alberta (Fig. 1), eventually emptying into Hudson Bay. The upper watershed study area (Fig. 2) is dominated by mountainous terrain, ranging in elevation from about 1200-3500 m asl. The Bighorn Hydroelectric Dam built in 1972 created Abraham Lake and serves as the pour point for the study basin. Although this area is only ~14% of the total watershed area above Edmonton, it is responsible for ~40% of average annual streamflow due to the large volume of water derived from snow and ice melt. The climatic regime can be characterized as continental, experiencing cold dry winters with wetter summers (Fig. 3). The hydrology of the area is snowmelt dominated with peak flows usually occurring in late spring/early summer (Fig. 4). Seven percent of the area is glaciated, and includes parts of Columbia Icefield in its northwestern extent (Fig. 2).

Peyto Glacier (~12 km²) is located in the southeast region of the UNSR basin (Fig. 2). This is one of the most intensively studied glaciers in North America, and being the primary benchmark glacier for the Canadian Rocky Mountains it offers continuous mass balance measurements since 1965 (Demuth & Keller, 2006). The detailed records of Peyto Glacier's mass balance and length variations will allow for verification of a mass balance model that will be applied to the watershed as a whole. Peyto experienced significant declines (-495 mm w.e. a⁻¹) in mass balance during the 20th century (Fig. 5).

Figure 5a: Peyto Glacier, c.1966

Figure 5b: Peyto Glacier, c. 2001

GLACIERS IN THE NORTH SASKATCHEWAN BASIN

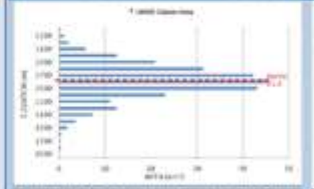


Figure 6: UNSR Glacier area-elevation Distribution. Peyto Glacier '65-'95 Equilibrium Line Altitude (ELA) (Demuth et al. 2006) in red.

Figure 7: Columbia Icefield Glaciers Area-Elevation.

Figure 8: Peyto Glacier Area-Elevation.

About 7% of the landcover in the UNSR basin is glaciated (~ 265 km²; Figs. 2 & 6). Glacier area-elevation relationships for Columbia Icefield Glaciers (Fig. 7) and Peyto Glacier (Fig. 8) are based on mid- 1980s landcover data (www.geogratis.ca). Area-volume scaling (DeBeer & Sharp, 2007) provides an estimate of total UNSR glacier volume of 21 km³, and average glacier depths of 122 m for Columbia Icefield and 75 m for Peyto Glacier. Many of the UNSR basin's glaciers have receded significantly since the surveys were done in the 1980s. Work is currently underway to define more recent glacial extents for use in verification of GENESYS model output (www.glims.org).

GENESYS HYDRO-METEOROLOGICAL MODEL

The GENESYS model will be used to spatially estimate the climate variables required to calculate glacier mass balance on a watershed scale. Byrne et al. (*in review*) simulated SWE over the complex terrain of the UNSR basin for the period 1960-2100 using GCM derived climate warming scenarios. Monthly temperature and precipitation lapse rates were derived from 1971-2000 PRISM climate normals, similar to a method used by MacDonald et al. (2009). SWE was simulated on a daily scale (Figs. 9 & 10) and compared well with observed conditions at the Bighorn Dam (Fig. 2). Future simulations showed a significant change in the timing of the onset of snowmelt across the watershed.

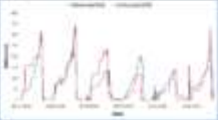


Figure 9: GENESYS model verification - daily snow pillow comparison.
(from Byrne et al. *in review*)

CLIMATE CHANGE IN THE NORTH SASKATCHEWAN BASIN

Figure 10: 1960-2100 trend in Total Annual Precipitation based on NCAR-B1 GCM.

Figure 11: 1960-2100 trend in Total Annual Precipitation based on MIRO-A1 GCM.

Figure 12: 1960-2100 trend in Total Annual Ice Days based on NCAR-B1 GCM.

Figure 13: 1960-2100 trend in Total Annual Ice Days based on MIRO-A1 GCM.

GENESYS model output for the UNSR basin was analyzed using climate-change indices developed by the WMO (Alexander et al. 2006). Figures 10-13 show decadal trends in Total Annual Precipitation (PRCP) and Ice Days (ID: $T_{max} < 0°C$) for 1960-2100, based on the NCAR-B1 and MIRO-A1B scenarios. These two indices are important for monitoring glacier health in the basin. PRCP drives the mass balance of glaciers by contributing to ice accumulation, while ID can be used as a proxy for the length of the glacial ablation period. Results show significant trends in PRCP and ID for both climate scenarios, with greater rates of change at high elevations.

GLACIER MASS BALANCE MODEL

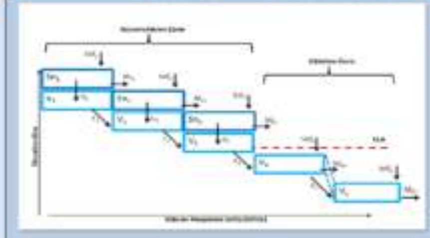


Figure 14: Conceptual diagram of glacier mass balance model (after Hirabayashi et al., 2010). Numbered components (1, 2, 3, 4,...n) represent the elevation bands in a given glacier. *Sn* is the snowpack, *V* is ice volume, *Snf* is snowfall, M_s is snowmelt, *G* is ice volume gained from previous year's snowpack, *F* is redistributed ice volume from glacier flow, and M_i is ice melt. *ELA* is the equilibrium line altitude where $G=M_i$.

Alpine glaciers act as barometers of climatic change, responding directly to longterm changes in temperature and precipitation with changes in mass balance and length. Glacier mass balance is defined as the difference between accumulation and ablation during the hydrologic year. A physically-based distributed mass balance model is currently being developed for application in the UNSR. GENESYS snowpack simulations will be used to calculate glacier accumulation and ablation. GENESYS uses GIS linked Terrain Categories (TCs) to spatially simulate hydro-meteorological variables across the watershed. The incorporation of elevation-based Glacier Response Units (GRUs) will allow the model to simulate the daily mass balance of ice volume across glacier surfaces (Fig. 14). Once the seasonal snowpack has been depleted, glacier ice will be melted with a hybrid degree-day model, using melt factors derived by Shea et al. (2009). Initial glacier volumes are calculated using the area-volume relationship defined in DeBeer & Sharp (2007). Snowpack that remains at the end of the hydrologic year will be converted to ice volume and will be spatially redistributed to lower glacier elevations for use in the following year's calculations. The model will be calibrated with Peyto glacier mass balance measurements and glacial extents derived from satellite imagery.

DISCUSSION

During the 20th century, glaciers across the globe experienced a severe decline (Lemke et al. 2007), including alpine glaciers in the Canadian Rocky Mountains. By 1995, Peyto Glacier had lost approximately 25% of its 1966 volume (Fig. 15), and around 60% of its 1896 volume (Demuth et al. 2006). Similarly, Jiskoot et al. (2009) found that the Clemenceau Icefield and Chaba Group glaciers, located just northwest of the study area, retreated an average of 14 m per year from 1850-2001. The Saskatchewan and Athabasca Glaciers in the CIG also experienced severe declines in recent decades (Fig. 16). Evidence suggests that recent warming has caused a change in glacier mass balance in the UNSR basin that is unprecedented during the Holocene (Comeau et al. 2009). Based on analysis of projected climate indices (Figs. 10-13) it is expected that glaciers in the region will continue to decline over the next century. The earlier onset of spring melt forecasted by GENESYS will result in a lengthening of the ablation season and a further reduction in glacier mass balance.

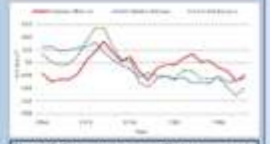


Figure 15: 5 yr moving averages of Peyto seasonal and net mass balance departures from 1966-95 means (Demuth et al. 2006).

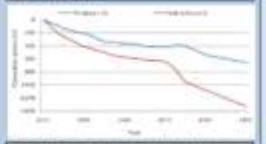
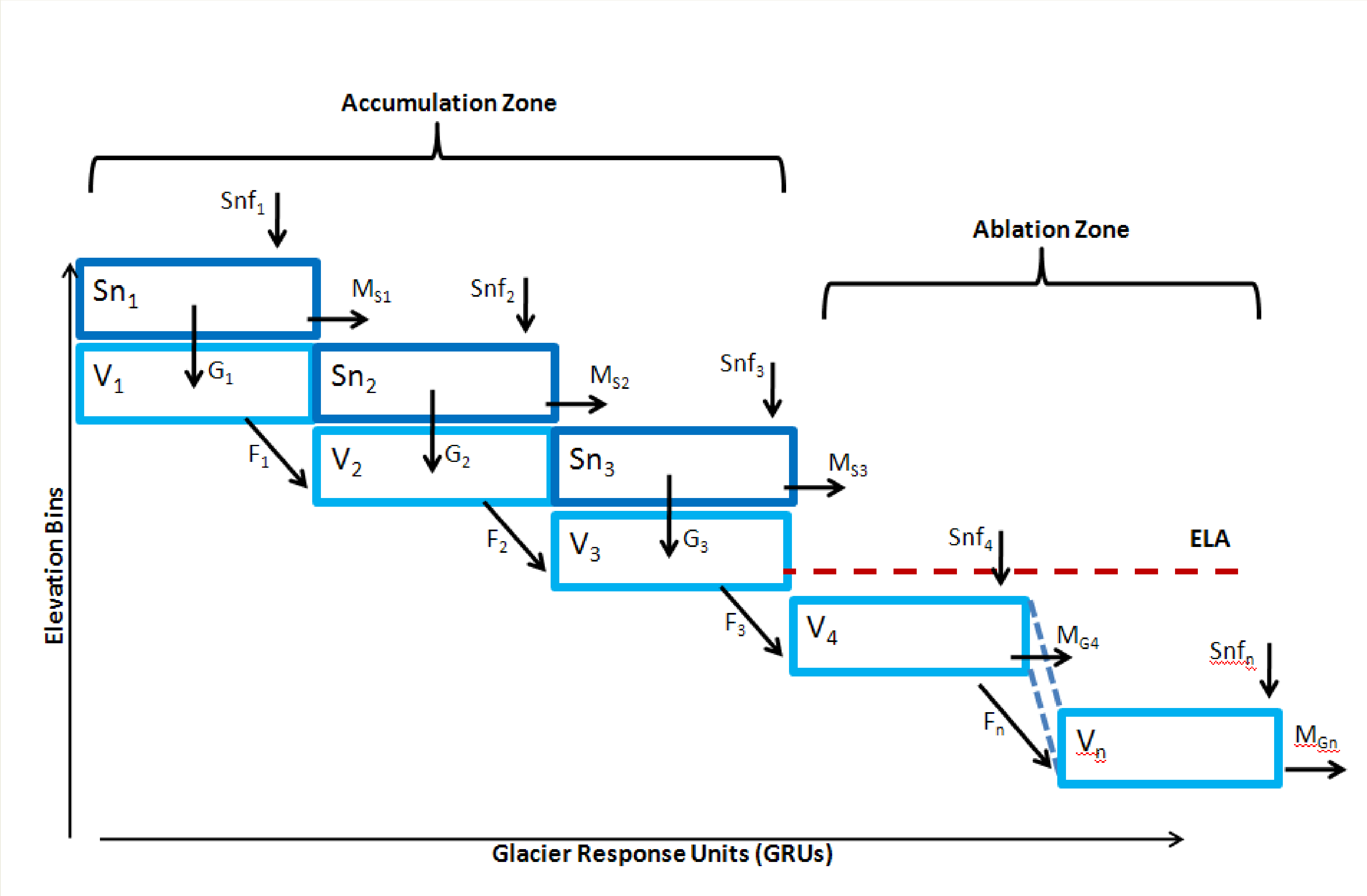


Figure 16: Cumulative retreat rates for the Athabasca and Saskatchewan glaciers (from www.wgms.ch).

REFERENCES

GLACIER MASS BALANCE MODEL

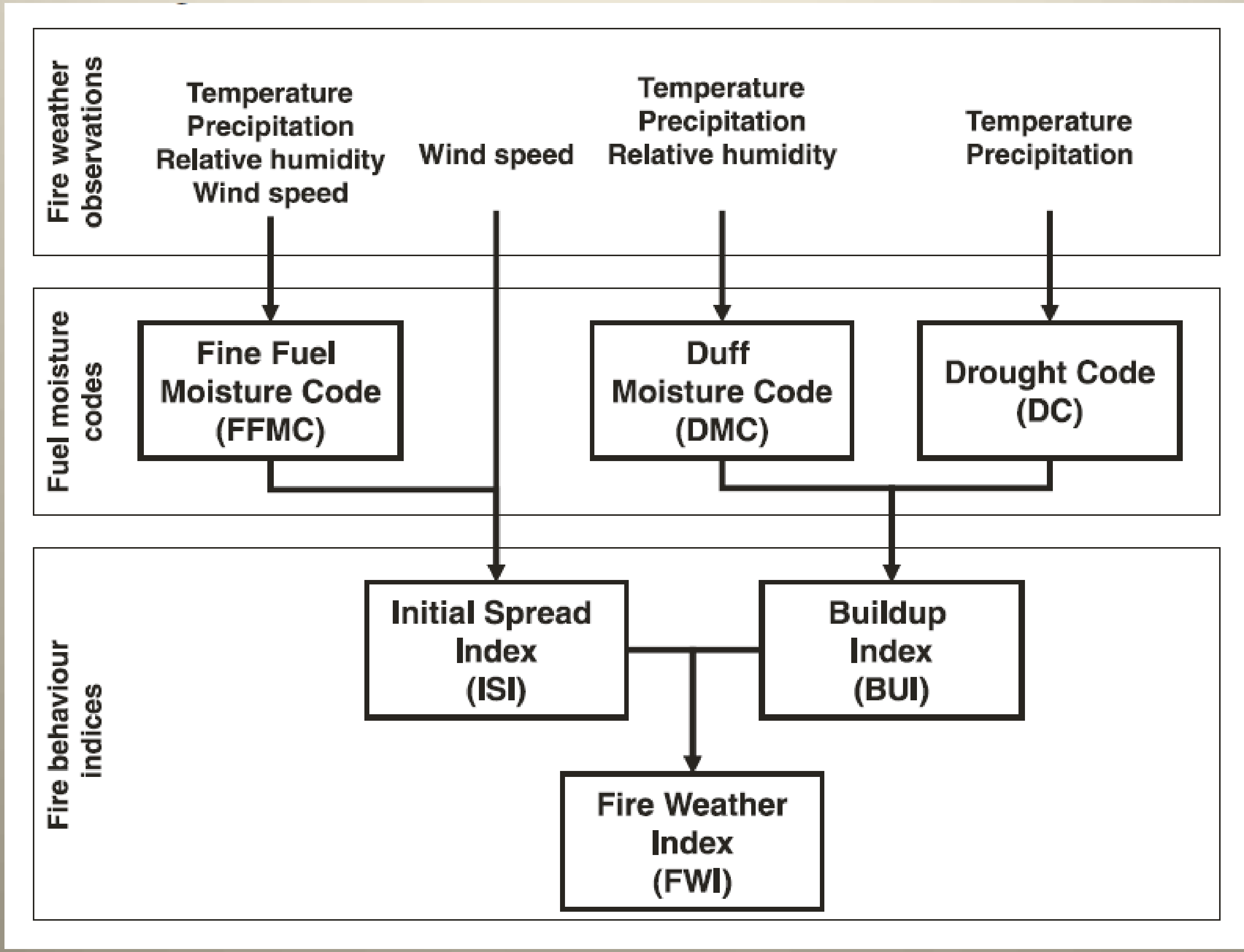


Conceptual diagram of glacier mass balance model (after Hirabayashi et al., 2010). Numbered components (1, 2, 3, 4,…n) represent the elevation bins in a given glacier. **Sn** is the snowpack, **V** is ice volume, **Snf** is snowfall, **MS** is snowmelt, **G** is ice volume gained from previous year's snowpack, **F** is redistributed ice volume from glacier flow, and **MG** is ice melt. **ELA** is the equilibrium line altitude where G=MG.

Sarah Dalla Vicenza MSc

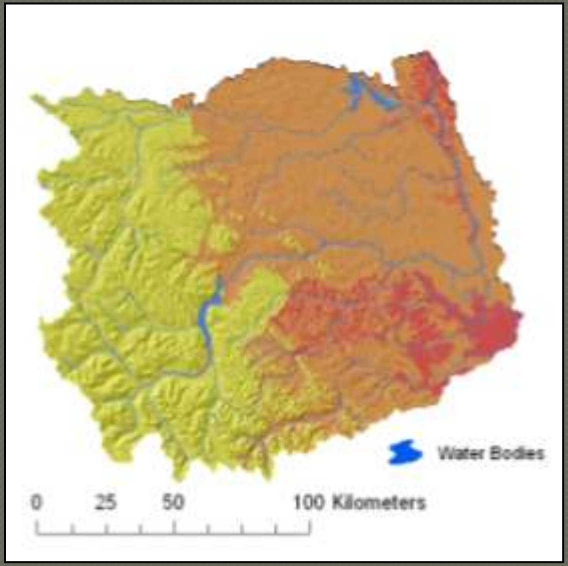
- Historical and Future Forest fire risk
  - Currently looking at Rocky Mountain eastern slopes

Canadian Fire Weather Index Adapted from Van Wagner (1987)



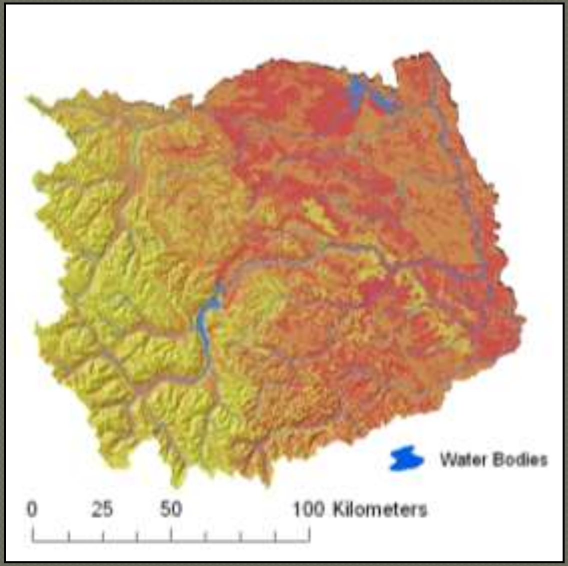
Fire Severity – Watershed Scale

Historical



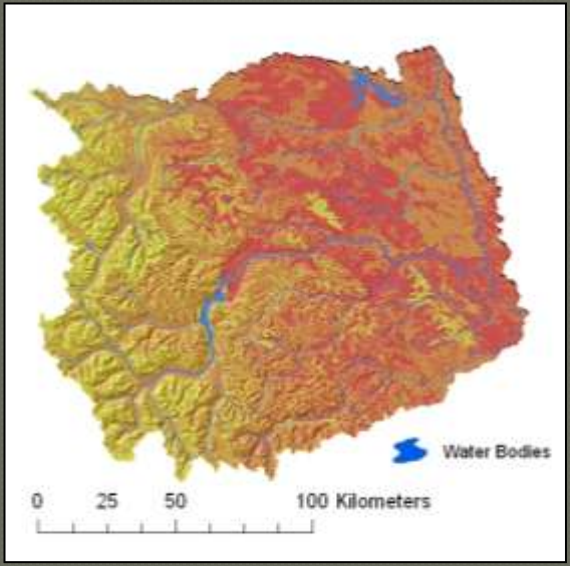
1961-1990

NCAR-B1



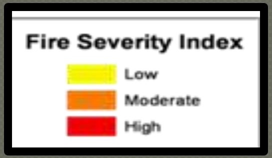
2070-2099

MIRO-A1B



2070-2099

Drought Indices?



Forest Fire Risk and Soil Moisture Dynamics in the Upper North Saskatchewan Watershed, Alberta

Sarah A. Dalla Vicenza, James M. Byrne, Matthew G. Letts

Water and Environmental Science Centre, University of Lethbridge, Lethbridge, Alberta

Abstract

The objective of this ongoing MSc research is to assess forest fire risk and soil water dynamics as part of an ongoing study assessing water quantity and quality in the Upper North Saskatchewan watershed. Forest fires are becoming an increasing concern as climate change advances on the eastern slopes of the Rocky Mountains of Alberta, as well as for mountain landscapes worldwide. Global climate change is expected to alter precipitation patterns and intensities and increase temperatures. Rising temperatures can cause decreases in soil moisture and as a result, drier forests and organic soils.

The goal of this research is to further develop a methodology for predicting potential changes in intensity and/or frequency of forest fires occurrence and extent in mountain environments. A forest fire risk subroutine is under development for the GENESYS model (Byrne et al., 2010 *in review*; MacDonald et al., 2009). GENESYS (GENerate Earth SYstems Science input) is a physically based hydrometeorological model that can be applied to simulate high resolution hydro-meteorology for watersheds in complex terrain using only recorded temperature and precipitation data for nearby climate stations. Climate change scenarios have been chosen to predict potential effects on future forest fire risk for over 900 distinct terrain categories.

Study Area

Figure 1: The upper North Saskatchewan watershed, Alberta.

The study region lies east of the continental divide of the Rocky Mountains in Alberta. The highest elevations contain substantial glacial ice cover. Most of the terrain below the glaciers is dense coniferous forests with mixed wood forests as elevation declines. Low elevations feature shrublands and some open prairie. Overall the study region covers 20,527 km^2. Here the main industries are oil and gas extraction, forestry, agriculture, and tourism. The climate is described as continental cool.

Methods

GENESYS Databases

GENESYS model output for the historical period (1960-2008) and for a range of GCM ensemble future scenarios (2010-2099) was available from previous work (Byrne et al in review). This project is developing a forest fire risk module for GENESYS based on applying the Canadian Forest Fire Weather Index System (CFFWIS).

CFFWIS

The CFFWIS model structure is shown in Figure 2. CFFWIS calculates a daily Fire Weather Index (FWI) and an associated Daily Severity Rating (DSR) or Seasonal Severity Rating (SSR). GENESYS output provides temperature, precipitation, and humidity data for all watershed terrains categories. Wind data was not available for the study area. Wind speed sensitivity tests of the model were carried out and are presented herein. For these preliminary model runs, a constant wind speed of 10 km/h was assumed.

DSR/SSR values: extreme ≥ 12 ; 4 ≤ high < 12 ; 1 ≤ moderate <4 ; low < 1

$$\text{Cumulative Sum} = \sum \text{DSR(year)} \qquad \text{SSR} = \left(\sum \text{DSR(year)}\right)/[illegible]$$

Figure 2: The Canadian Forest Fire Weather Index System. Adapted from Van Wagner (1987).

Soil Moisture (SM)

$$SM_{(t)} = SM_{(t-1)} + P_{(t)} - I_{(t)} - ET_{(t)} - R_{(t)}$$

Where P is precipitation, I is canopy interception, ET is evapotranspiration, R is runoff, and t is day.

General Circulation Models (GCMs)

Two GCMs were chosen for this study; NCAR-B1 and MIRO-A1B. Both GCMs predict an increase in temperature and precipitation in future decades. NCAR-B1 is more conservative - a 2°C temperature increase and 15% increase in precipitation by 2050. MIRO-A1B estimates a 3.5°C temperature increase and almost 25% increase in precipitation by 2050.

Results

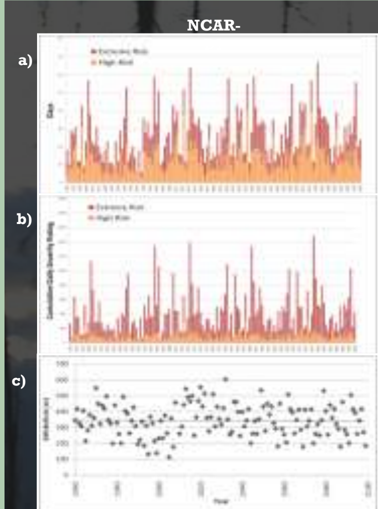


Figure 3: 1960-2099 using the NCAR-B1 GCM showing a) annual count of days with high or extreme fire risk; b) annual cumulative sum of high and extreme daily severity ratings; c) annual soil moisture deficit in millimetres.

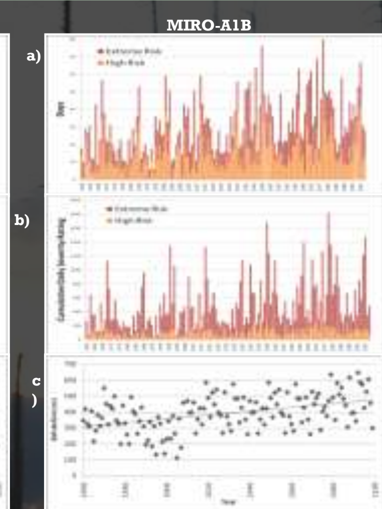


Figure 4: 1960-2099 using the MIRO-A1B GCM showing a) annual count of days with high or extreme fire risk; b) annual cumulative sum of high and extreme daily severity ratings; c) annual soil moisture deficit in millimetres.

Wind Sensitivity

Wind speed data was not available for this study. The sensitivity of the CFFWIS model was tested using constant wind speeds of 0, 10, 20, and 30 km/h. Figure 5 illustrates a wind sensitivity test for the year 1960 at an elevation of 2000 metres.

Figure 5: Sensitivity of the CFFWIS model to wind speed.

Discussion

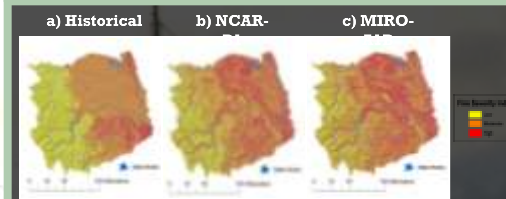


Figure 6: Average Seasonal Severity Rating for a) 1961-1990; b) 2070-2099 using the NCAR-B1 scenario; c) 2070-2099 using the MIRO-A1B scenario.

- Both the NCAR-B1 and the MIRO-A1B scenarios show an upward trend in the count of days with high or extreme daily severity risk (Figures 3a and 4a) as well as the cumulative daily severity rating (Figures 3b and 4b), with the MIRO-A1B showing a much more pronounced rise through 2099.
- Figure 3c indicates little change in soil moisture deficit for the NCAR-B1 GCM which conforms to the fire risk index charts. Similarly, Figure 4c shows a rise in soil moisture deficit which coincides with the rise in both the annual count of days with high or extreme risk and the cumulative daily severity rating.
- Figure 5 demonstrates the sensitivity of the CFFWIS model to wind speed. It is evident that a change in wind speed can greatly alter the daily severity rating.
- Figures 6 a, b, and c display the change across the watershed in seasonal severity rating. While both GCMs predict an increase in average SSR, the MIRO-A1B shows a greater area of high risk.

Future Directions

Future Directions:

- Developing a wind speed simulator from NCEP 700 and 850 mbar data. This will include linking NCEP data to regional climate station wind data.
- Statistical analysis of fire risk simulations.
- Testing the CFFWIS for a larger range of GCMs.

References

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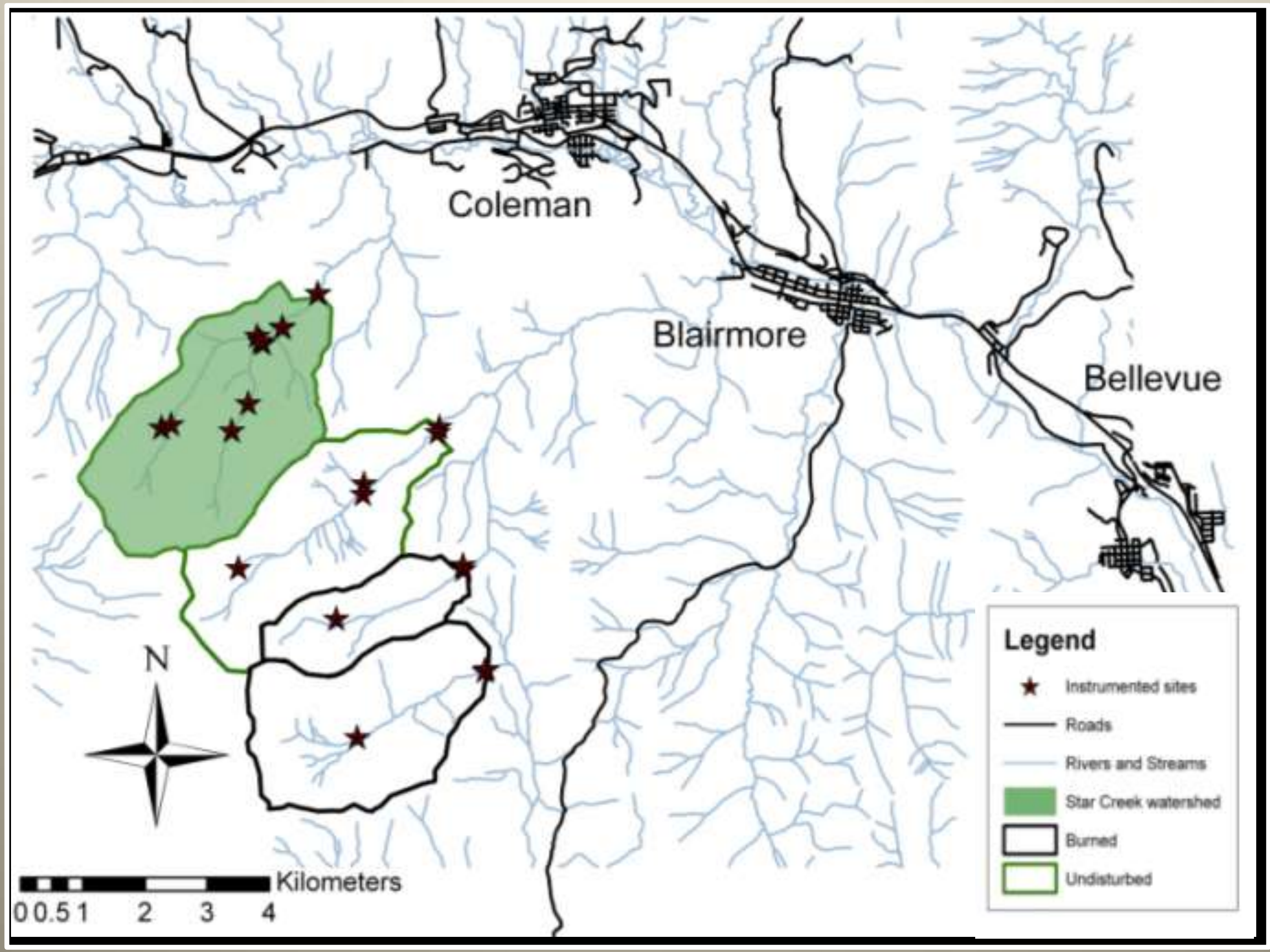
MacDonald, R.J., J.M. Byrne, S.W. Kienzle (2009). A physically based daily hydrometeorological model for complex mountain terrain. *Journal of Hydrometeorology, 10,* 1430-1446.

Van Wagner, C.E. (1987). Development and Structure of the Canadian Forest Fire Weather Index System. Can. For. Serv., Ont. For. Tech. Rep. 35.

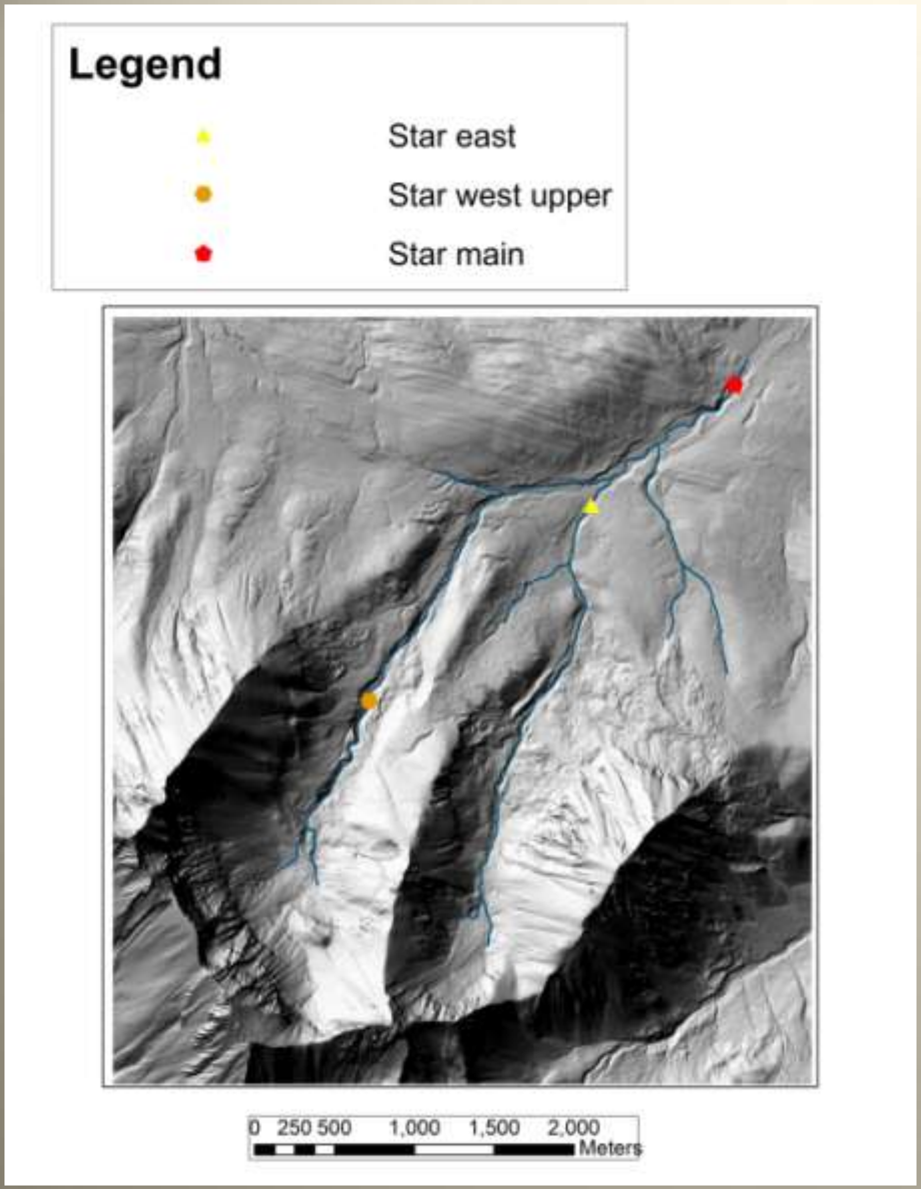
Ryan MacDonald PhD Research

Stream temperature response to Environmental Change

Study site



Coleman
Blairmore
Bellevue
N
Kilometers
0 0.5 1 2 3 4
Legend
Instrumented sites
Roads
Rivers and Streams
Star Creek watershed
Burned
Undisturbed



Hourly measurements of:
Stream temperature
Air temperature
Relative humidity
Wind speed/direction
Net radiation
Stream stage

Routine sampling of:
Discharge
Groundwater level
Hyporheic water level

Acknowledgements

- EPCOR and Natural Sciences and Engineering Research Council of Canada (NSERC) for funding
- University of Lethbridge
- Alberta Conservation Association
- Trout Unlimited Canada
- Alberta Water Research Institute
- Canadian Water Network