Evaluation of the Monthly Drought Code as a metric for fire weather in a region of complex terrain and uncertainties in future projections

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Changes in both temperature and precipitation due to climate change will have a significant impact on future fire weather severity. The availability of a simple but skillful fire weather index would increase our ability to assess the magnitude and uncertainties of these impacts. We evaluated the Monthly Drought Code as a metric for fire weather and generated a suite of future projections of the Monthly Drought Code for regions throughout southeast British Columbia using statistical downscaling. Significant correlations between the Monthly Drought Code calculated at five airport stations and annual area burned were found with a maximum R^2 of 0.68. These results compare favourably to: its own input variables; more sophisticated models; and other fire weather indices. Reconstruction skill of the historical Monthly Drought Code using statistical downscaling varied (R^2 = 0.36 to 0.72), with the best results at drier stations. A suite of future projections was created using six global climate models and three emission scenarios. Projected changes range from insignificant changes to increases, the latter suggesting important shifts in fire frequency. This range was primarily due to a large ensemble spread in precipitation projections across climate models.

1 INTRODUCTION

Wildfire is an integral part of ecosystems. It is a major source of often positive disturbance in North American forests which plays a critical role in determining ecosystem properties such as age structure, species abundance, and landscape patterns. Wildfire activity is, in turn, strongly dependent on climate. Globally, spatial distributions of wildfire occurrence are strongly dependent on spatial patterns in temperature and precipitation, as these variables determine both the fuel moisture and fuel availability of a particular ecosystem (Krawchuk et al. 2009). Previous studies have demonstrated relationships between a variety of climate variables (such as temperature, precipitation and drought severity) and area burned throughout western North America (e.g., Littell et al. 2009). As well, a variety of studies have linked strong anti-cyclonic conditions (i.e., "blocking highs") to enhanced fire activity (e.g., Skinner et al. 1999).

Given the strong connection between climate and wildfire, it is likely that a changing climate will have a substantial effect on future wildfire severity and frequency. Historically, annual values of total area burned have increased across many regions of North America over the last 50 years (Mouillot and Field, 2005). Some of this increase can be attributed to human activities of the last century, including changes in fire suppression policy, logging practices, and increased population density (Allen et al. 2002). However, in some cases fire suppression has not affected natural fire regimes (Schoennagel et al. 2004). Moreover, Gillett et al. (2004) were able to attribute some of the historical increase in wildfire across Canada to anthropogenic global warming.

Numerous studies have attempted to provide future projections of wildfire severity or frequency (see Flannigan et al. 2009 for a review and IPCC 2012). In general, these studies use global climate models (GCMs) to provide future climate information from which projected changes in fire weather or actual wildfire activity are inferred. Techniques used in the studies vary in sophistication. Some studies used raw GCM output (e.g. Flannigan et al. 1998), while others have used a "Delta" downscaling approach where monthly GCM anomalies are used to adjust historical daily time-series of meteorological observations (e.g., Nitschke and Innes 2008). A variety of studies have used either linear or non-linear regression to draw connections between meteorological variables and wildfire severity (Balshi et al. 2009; Krawchuk et al. 2009; Le Goff et al. 2009; Wotton et al. 2010). A large number of studies use the Canadian Fire Weather Index system (FWI; Van Wagner, 1987), which employs standard meteorological observations to produce a variety of indices meant to represent fire weather and potential fire intensity. Although these studies differ in technique, study area, and predictor variables, the majority of the results suggest that there will be substantial increases in fire severity or frequency in North America through the 21st century.

This report evaluates the effectiveness of the Monthly Drought Code (MDC), which was developed by Girardin and Wotton (2009), as a simple fire weather index within the complex terrain of southeast British Columbia (BC), Canada using five valley bottom weather stations. It is tested at both the local (10^4 km^2) and regional (10^5 km^2) scale and projections of this fire weather index are evaluated for potential future climates. This report also discusses a number of issues pertinent to creating future projections of fire weather for BC.

First, we calculate correlations between local and regional AAB values and the MDC. These correlations are compared to results from more complicated statistical models, the MDC input variables (precipitation and temperature), and previously used fire weather indices, many of which require hourly or daily data of temperature, precipitation, moisture, and surface wind speed. Using monthly data allows us to avoid errors in simulating complex local and mesoscale processes that often dominate the daily variability of summer weather conditions. These issues are especially pertinent for precipitation and wind speed (van der Kamp et al. 2012; Bürger et al. 2012). Moreover, the use of monthly data, which are more readily available from databases of both historical observations and GCM projections, will make application of our procedure to other regions and GCMs more feasible. Favourable results would suggest that the MDC provides a simple tool for estimating inter-annual variability and changes in wildfire climatology.

Second, we examine the utility of a small number of weather stations for predicting AAB over the broad region of southeast BC (on the order of 10^5 km^2). Previous work suggests that large synoptic and continental scale weather patterns play a large role in determining seasonal fire weather levels in BC and the Pacific Northwest (Heyerdahl et al. 2008). This suggests that when calculating fire weather indices, spatial coverage provided by interpolation or high resolution climate models may be less important and that a small number of high-quality, valley bottom stations may be able to provide enough information to capture these broad synoptic-scale features that seem to be driving fire activity in our region.

Finally, we produce projections from six global climate models and three emission scenarios that represent a wide range of inter-model variability seen in future precipitation projections. Many studies of future wildfire severity in Canada have used smaller ensembles of projections. Although larger ensembles of GCMs have been applied to wildfire projections elsewhere (e.g., Bergeron et al. 2010 and McCoy and Burn 2005), such a technique has not previously been applied to BC where there is disagreement among GCMs over whether the future will see increases or decreases in summer precipitation. Our study examines the implications of this uncertainty in future precipitation levels on fire weather projections. It should be noted that we restrict our projections to the MDC, and we do not attempt to project area burned into the future. The primary reason for this is that we want to avoid extrapolating any historical relation we develop between the MDC and AAB due to potential future changes in suppression activity, population density and vegetation patterns within our study region.

This paper begins with a description of the geography, climatology and wildfire history of the study region in Section 2. We outline our methods in Section 3 where a brief overview will be followed by a more detailed description of the data and methods including: description of the MDC; an overview of our statistical downscaling procedure; and details of the meteorological observations, historical fire dataset, and GCMs used. Results are presented in Section 4 and include: assessment of the MDC as a predictor of wildfire activity; the skill of our downscaling method in simulating historical observations of precipitation, temperature and MDC; and features of the future projections of MDC. A discussion of the results is provided in Section 5 and concluding remarks in Section 6.

2 STUDY AREA

Southeast BC (Figure 1) is characterized by a large range in elevation and significant topographic relief with steep and narrow valleys. The MDC was calculated from temperature and precipitation observations at five long-term Environment Canada stations located in valley bottoms throughout the region (Canadian Daily Climate Data archive http://climate.weatheroffice.gc.ca/prods_servs/index_e.html). Additionally, operational fire weather indices were acquired from two long-term fire weather stations maintained by British Columbia's Ministry of Forests, Lands and Natural Resource Operations (http://bcwildfire.ca/Weather/stations.htm). Additional station information is provided in Table 1.

Being directly east of the Coastal Mountain Range, the western part of our study region (e.g., Kelowna and Penticton) has relatively low precipitation rates due to the rain shadow effect. Further east and north sees higher precipitation levels along the windward side of the Rocky Mountains due to orographic lifting of moist air and the accompanying atmospheric instability (e.g., Blue River). Precipitation rates are also low within the Rocky Mountain Trench, a major valley running parallel to, and located around 100 km west of, the BC-Alberta border (e.g., Cranbrook). Average temperatures vary substantially, most strongly following elevation. Due to these significant climatological gradients, the region contains a number of distinct fire regimes, ranging from the high-frequency, low severity regime of ponderosa pine (Pinus ponderosa) forests to the low-frequency, high severity regime of the subalpine forests.

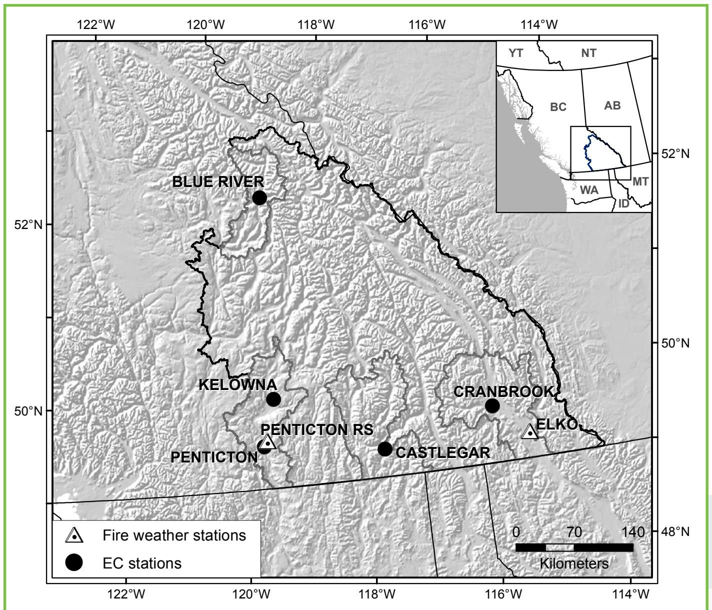

Figure 1: Map of study area. Watershed outlines used for calculating annual area burned values are shown. The grey outlines indicate watersheds used for local area burned values, while the thick black outline shows the larger region of the Columbia, Okanagon and Upper Thompson watersheds that were used to calculate the regional area burned.

Table 1: Meteorological and fire weather stations used in this study (Locations are shown in Figure 1).

Station Name	Latitude (°N)	Longitude (°W)	Elevation (m)	Station ID[1]	WMO ID[2]	TC ID[3]	Station Coverage
Environment Canada Stations							
Castlegar	49.3	-117.63	495	1141455	71884	YCG	1970 – 1992; 1998 – 2009
Blue River	52.13	-119.29	682.8	1160899	71883	YCP	1970 – 2009
Kelowna	49.96	-119.38	429.5	1123970	71203	YLW	1970 -2004
Cranbrook	49.61	-115.78	940	1152102	71880	YXC	1970 – 2009
Penticton	49.46	-119.6	344.1	1126150	71889	YYF	1970 – 2009
Fire Weather Stations							
Penticton RS	49.52	-119.55	427	328	N/A	N/A	1970 - 2009
Elko	49.28	-115.24	775	412	N/A	N/A	1970 - 2009

[1] Station IDs are taken from the different naming conventions of the two networks
[2] WMO = World Meteorological Organization
[3] TC = Transport Canada

Despite these strong climate gradients, at the monthly and seasonal time scale both precipitation and temperature have large covariance structure. I.e., inter-station correlations are quite high for the distances being considered here (Hansen and Lebedeff, 1987). This is especially true for temperature. As well, it has been shown that synchronous drought conditions across western North America can in turn lead to synchronicity in fire activity over a broad area such as our study region (Heyerdahl et al. 2008). This is due to the strong influence of synoptic to continental scale systems on surface temperatures (e.g., "blocking highs").

There is a relatively large inter-model spread in future precipitation projections for the region. Generally, there is strong agreement between GCMs that precipitation will decrease in the southwest of the United States and Mexico and increase in the northern boreal region. However, our study region lies between these two regions, leading to larger disagreement among models (Christensen et al, 2007: section 11.5.3.2). Consequently, this region will provide an extreme case in which we can analyse the impact of the spread in precipitation projections on uncertainties in future fire weather.

Our choice of study area was also motivated by the unique wildfire history of B.C.; both Taylor et al. (2007) and Meyn et al. (2010b) document negative trends in wildfire activity within the province, in contrast to the general positive trends for Canada as a whole. A number of studies (Girardin and Wotton, 2009; Meyn et al. 2010b) have pointed to historical increases in precipitation within southwestern Canada as a possible explanation for these decreases in wildfire activity. Another possible explanation points to the increase in fire suppression activities of the last half-century. However, suppression activity is less effective within the high density forests found within the higher regions of our study area, such as the Englemann Spruce and Subalpine Fir biogeoclimatic zones. In these areas a high-severity fire regime leads to large, low-frequency stand-replacing crown fires, which are difficult to suppress and are little affected by previous suppression activity. (Schoennagel et al. 2004).

3 METHODS AND DATA

3.1 Overview

The first portion of the study involved testing the MDC's ability as a predictor of seasonal wildfire severity. For each station, the local wildfire activity was estimated by calculating the annual area burned (AAB) during the fire season within each station's local watershed (shown in Figure 1). This local AAB was then regressed against the MDC time series at each station calculated separately for each month (May to September) and for the summer (June, July and August). As well, a regional MDC, calculated as an average across all five stations, was regressed against the AAB summed across the larger southeast BC region indicated in Figure 1. Finally, this procedure was repeated for both temperature and precipitation. Additionally, we acquired time series of FWI indices from two long-term fire weather stations located near two of our EC stations (See Figure 1). Wildfire managers

Table 2: Summary of FWI indices acquired from fire weather stations for comparison with the MDC.

Index	Purpose	Required Input Variables	Notes	
Fine Fuel Moisture Code	Moisture estimate of the litter layer at the top of the soil	Temp/RH/Wind/Precip	Drying lag-time of ~16 hours	(Lawson et al., 2006)
Duff Moisture Code	Moisture estimate of the loosely compacted duff layer below the litter later	Temp/RH/Precip	Drying lag-time of ~12 days	(Muraro and Lawson, 1970)
Drought Code	Moisture estimate of the deep compact organic layer	Temp/Precip	Drying lag-time of ~52 days	(Turner, 1972)
Fire Weather Index	Estimate of possible fire severity	FFMC/DMC/DC/Wind		(Van Wagner, 1987)
Monthly Severity Rating	Estimates difficulty of potential fire suppression	FWI	Log-transform of FWI	(Stocks et al., 1998)
Seasonal Severity Rating	Seasonal average of Monthly Severity Rating	MSR		(Flannigan and Van Wagner, 1991)

Table 3 – Summary of the global climate models used in this study.		
Model ID	Modelling Centre and Model	Primary Reference
CGCM	Canadian Centre for Climate Modelling and Analysis (Canada), CGCM3.1 (T47)	Scinocca et al (2008)
CNRM	Météo-France / Centre National de Recherches Météorologiques, CNRM-CM3	Salas-Melia et al (2005)
ECHAM	Max Planck Institute for Meteorology (Germany), ECHAM5/MPI-OM	Roeckner et al (2006)
GFDL	NOAA Geophysical Fluid Dynamics Laboratory (USA), GFDL-CM2.1	Delworth et al (2006)
MIROC	Center for Climate Systems Research (Japan), MIROC 3.2 (medium resolution	K-1 model developers (2004)
CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australia) CSIRO – MK 3.0 (T63)	Rotstayn et al. (2010)

calculate these indices on an operational basis. The regression against AAB was repeated for each FWI index. All variables and residuals were checked for any non-normality or auto-correlation that would violate the assumptions underlying the regression analysis.

The second part of the study involved generating a suite of MDC projections at all five stations using temperature and precipitation projections from six GCMs and three emissions scenarios, using statistical downscaling, the details of which are provided below. In order to test our downscaling procedure we compared the results forced by the NCEP Reanalysis 1 product (Kalnay et al. 1996) to historical observations. The downscaling algorithm was trained using data from 1970 to 1990 and we tested the ability of our downscaling technique by calculating correlations between simulated and observed data for the independent evaluation dataset of 1991 to 2006. In a final step, the sensitivity of future MDC anomalies to temperature and precipitation changes was analyzed.

3.2 The Monthly Drought Code

The MDC was developed by Girardin and Wotton (2009) as a simplified version of the original Drought Code (DC), which requires noon observations of precipitation and temperature. Please refer to their paper for a detailed description of both indices. In brief, the DC, a component of the Canadian Fire Weather Index system, is a "bookkeeping" index in which moisture is added to the previous day's value through precipitation and removed through evaporation, which is a representation via a temperature function. The DC was designed to provide a moisture estimate of the deep compact organic layer. Consequently, it has a slow drying rate with a drying lag-time (defined as the time it takes the soil to lose 1-1/e of its moisture as it dries towards an equilibrium state) of around 52 days. The DC usually reaches a maximum value in late August or early September. Based on experimental work (e.g., de Groot et al. 2009) and the experience of fire managers, "low" DC values generally fall below 200, while values greater than 400 are associated with "extreme" fire activity where most of the available fuel is likely to burn (Girardin and Wotton, 2009). There are a number of additional FWI indices that we will also be using as predictors of wildfire activity, the results of which we will compare to the MDC. These indices are summarized in Table 2.

Because of its slow drying rate, the DC provides an indication of the overall seasonal moisture deficit and contains little information about fire weather severity at the daily time scale despite using daily data. Consequently, as Girardin and Wotton (2009) pointed out, it makes sense that a version of the DC using monthly mean data, i.e., the MDC, would capture the same information as the daily version. The MDC is calculated in a similar fashion to the DC. The calculation starts with the previous month's value to which a steady rate of evapotranspiration (which is a function of the monthly mean daily maximum temperature in the equation) is applied for the first half of the month. That is, it is assumed that the daily maximum temperature is constant for the entire month. The total month's precipitation is then assumed to accumulate entirely at the middle of the month. The same rate of evapotranspiration is then applied to the last half of the month, resulting in the new MDC value. Girardin and Wotton (2009) found the MDC to correlate strongly with monthly averages of the original DC (R^2 values ranged from 0.87 to 0.95).

Table 4: Correlations (R^2) between monthly and summer (JJA) values of daily maximum temperature, precipitation, and MDC observed at the Environment Canada stations and the AAB calculated for each station's local watershed shown in Figure 1. Correlations that are significant at the 5% level are indicated in bold.

	May			June			July			August			September			JJA		
Station	Tmax	Pr	MDC	Tmax	Pr	MDC	Tmax	Pr	MDC	Tmax	Pr	MDC	Tmax	Pr	MDC	Tmax	Pr	MDC
Castlegar	0.00	0.09	0.07	**0.14**	**0.23**	**0.25**	**0.32**	**0.15**	**0.44**	**0.24**	**0.21**	**0.61**	**0.04**	0.01	**0.35**	**0.52**	**0.54**	**0.58**
Blue River	0.06	0.02	0.03	0.06	0.00	0.01	**0.23**	0.10	**0.15**	**0.17**	**0.12**	**0.24**	**0.02**	0.01	**0.12**	**0.31**	0.11	**0.18**
Kelowna	0.02	**0.27**	**0.23**	**0.11**	**0.15**	**0.36**	**0.15**	**0.12**	**0.34**	0.08	0.09	**0.39**	**0.00**	0.01	**0.35**	**0.27**	**0.27**	**0.42**
Cranbrook	0.00	**0.14**	**0.14**	**0.17**	**0.22**	**0.34**	**0.29**	**0.17**	**0.50**	**0.16**	0.04	**0.53**	**0.04**	0.08	**0.22**	**0.55**	**0.33**	**0.53**
Penticton	0.01	0.04	0.06	**0.11**	**0.12**	**0.21**	**0.10**	**0.11**	**0.29**	**0.08**	**0.09**	**0.36**	**0.01**	0.06	**0.35**	**0.19**	**0.24**	**0.34**
Mean	**0.02**	**0.11**	**0.11**	**0.12**	**0.14**	**0.23**	**0.22**	**0.13**	**0.34**	**0.15**	**0.11**	**0.42**	0.02	**0.03**	**0.28**	**0.37**	**0.30**	**0.41**

The DC and MDC must be initialized at the beginning of each season. The initialization date is determined operationally based on snow disappearance and/or temperature levels. If the soil was saturated during the preceding winter, the DC is "reset" to a default value of 15. If not, a standardized method using soil type information and winter precipitation is required to determine the initialization value (Lawson and Dalrymple 1996). However, due to the paucity of soil information and for the sake of simplification, Girardin and Wotton (2009) assumed that the soils are fully recharged by May 1st and began each season with a default value of 15. We will adopt the same procedure here. However, it should be noted that while this assumption is generally valid for the boreal region (Girardin and Wotton's main focus) it is likely less accurate for some of the drier regions of our study area. We will test the impact of this approximation by comparing the predictive power of our MDC values to that of operationally derived DC values, which include overwintering calculations.

3.3 Future projections

Projections of future climate were obtained from six GCMs, listed in Table 3. We have attempted to select a suite of GCMs that is representative of the spread in future temperature and precipitation seen in the ensemble of models in the World Climate Research Programme's (WCRP) Coupled Model Intercomparison Project Phase 3 (CMIP3; Meehl et al. 2007) dataset (Figure 2). As well, the models used here have performed relatively well when compared to historical observations over the globe and western North America (Radic and Clarke, 2010). Also shown in Figure 2 are projections for three older models (the first two generations of the Canadian GCM, CGCM1 and CGCM2, and HADCM3) that have been used in a majority of previous studies on future wildfire severity in Canada.

Three emission scenarios developed for the Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC) were used for this analysis. The A1B scenario stipulates emissions which lead to moderate temperature increases relative to the range of all TAR scenarios, while the A2 scenario falls in the higher end of that range. The B1 scenario describes a low emission future. We calculate anomalies relative to 1961 to 1990 for two periods, 2046 to 2065 ("2050s") and 2081 to 2100 ("2080s").

GCM scenarios are downscaled to each of the five stations using the Bias Correction Spatial Disaggregation (BCSD) procedure described by Wood (2004). This technique aims to bias correct percentiles of his-

Table 5: Correlations (R^2) between DC calculated at the fire weather stations and the AAB calculated for each station's local watershed shown in Figure 1. Correlations that are significant at the 5% level are indicated in bold.

Station	May	June	July	August	September
Penticton RS	0.00	0.02	0.10	**0.16**	0.11
Elko	0.00	0.01	0.05	**0.30**	**0.37**

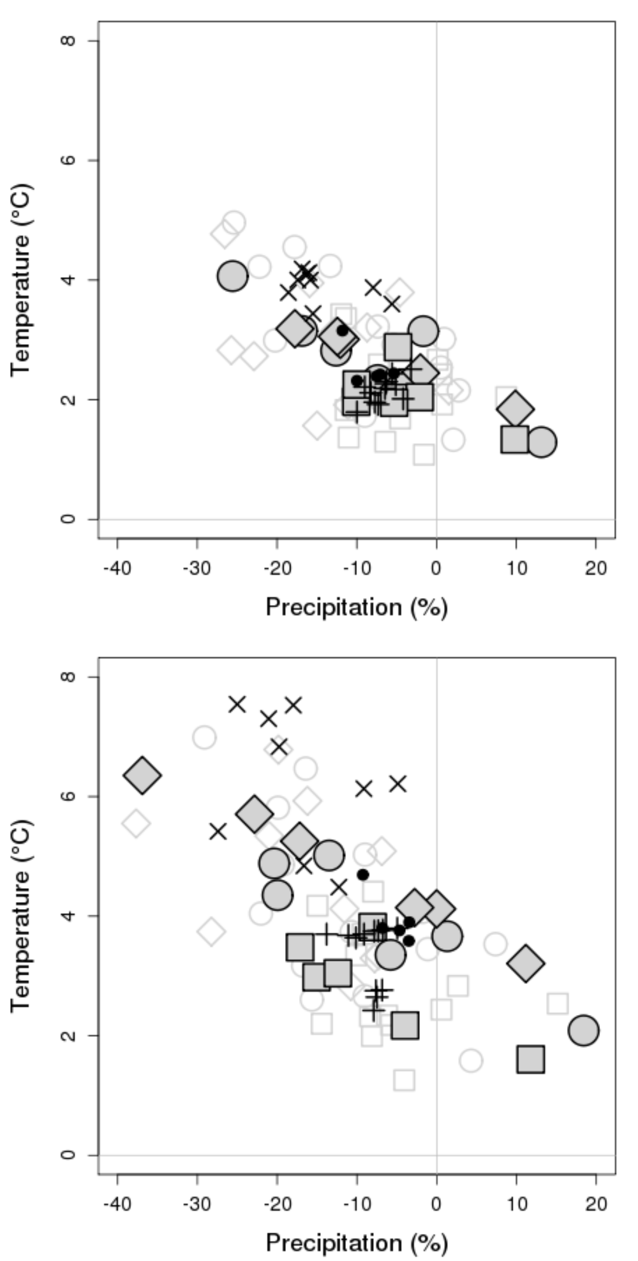

Figure 2: JJA mean of daily maximum temperature and JJA precipitation anomalies for the 2050s (top) and 2080s (bottom) for the GCMs used in this study (filled grey symbols), as well as all available GCMS in the CMIP3 ensemble (unfilled light gray symbols). Emission scenarios A2 (diamonds), A1b (circles) and B1 (squares) are included. Also included are anomalies from the non-CMIP3 GCMS, CGCM1 (black dots), CGCM2 (black plus signs), and HADCM3 (black X's) for all available scenarios.

torical GCM output to ensure that the monthly mean and variances of the GCMs match the observed data via quantile mapping. BCSD is a widely applied statistical downscaling technique, which has been shown to be one of the more successful approaches for downscaling course resolution GCM results (Bürger et al. 2012) and has been shown to provide value in tracking daily fire danger indices in the western US (Abatzoglou and Brown, 2012). BCSD's strengths include the ability to capture projected changes across all percentiles (Werner 2011).

3.4 Historical wildfire data

A database of observed wildfires in BC from 1950 onwards was downloaded from the Province of BC's geographic data distribution service (www.data.gov.bc.ca). The database includes location, date of discovery, cause, and final size information. Although there are likely artifacts in the database due to changes in observational density, an analysis by Meyn et al. (2010b) found no significant artifacts within our study region.

4 RESULTS

4.1 MDC as predictor of wildfire activity

May to September and JJA averages for MDC, maximum daily temperature, and precipitation were calculated at the Environment Canada stations and regressed against the log of AAB for each station's local watershed shown in Figure 1. Correlation strengths are reported as Coefficient of Determination (R^2) values and are presented in Table 4. Overall, the MDC shows the highest correlations of the three variables, with the best results seen in August (R^2 ranges from 0.24 at Blue River to 0.61 at Castlegar). These August relationships are shown in Figure 3. In some individual cases the maximum daily temperature correlates more strongly than the MDC, notably for the Blue River station in JJA (Table 4).

This procedure was repeated for the two fire weather stations using monthly averages of the six operational fire weather indices presented in Table 2. For the sake of brevity only the results for the DC are shown in Table 5. Monthly means of the more complex daily DC show smaller correlations with AAB than the MDC calculated at the closest Environment Canada station and correlations are significant only for the Elko station. Moreover, the MDC outperforms the other operational fire weather indices in the majority of cases. The Duff Moisture Code, Initial Spread Index, Fire Weather Index and Monthly Severity Rating at the Elko station show better correlations than the MDC (the maximum R^2 value being 0.66 for the August Duff Moisture Code) but no such improvement is seen at the Penticton RS station (not shown).

Table 6: Correlations (R^2) between the monthly and summer (JJA) values of daily maximum temperature, precipitation, and MDC averaged across all five stations and the regional AAB calculated for the larger southeast BC region shown in Figure 1. Correlations that are significant at the 5% level are indicated in bold.

Variable	May	June	July	August	September	JJA
Tmax	0.03	0.09	**0.36**	**0.28**	0.00	**0.51**
Pr	**0.14**	**0.14**	**0.25**	**0.23**	0.00	**0.40**
MDC	**0.12**	**0.23**	**0.50**	**0.68**	**0.48**	**0.61**

AAB was also calculated for the entire region of southeast BC, which we took to be comprised of the Canadian portion of the Columbia River watershed (excluding the Similkameen watershed) and the upper region of the Thompson River (see Figure 1). This regional AAB was regressed against the five-station averages of MDC, temperature and precipitation, the results of which are presented in Table 6. The August value of this regional MDC correlates most strongly with the regional AAB (R^2 = 0.68), followed by JJA MDC (R^2 = 0.61) and the JJA daily maximum temperature (R^2 = 0.51).

Comparing the MDC correlations in Table 4 and Table 6 across months, it is clear that the August value is

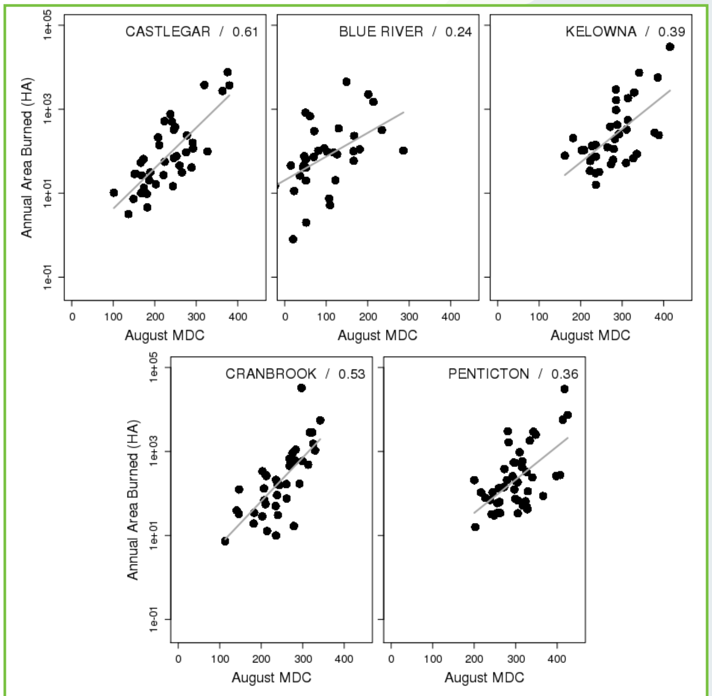

Figure 3: Correlation between the log of the AAB and the August MDC calculated at the EC stations for 1970 to 2009. AAB was calculated by including all fires within each station's local watershed, which are shown in Figure 1. R^2 values are provided next to the station name. Regression lines are shown in grey.

the best predictor of wildfire severity within our study region. The MDC is most sensitive to the average precipitation of the last three months and the temperature of the current month (analysis not shown here). This is a direct consequence of the MDC algorithm. Therefore, the following results will focus on the August temperature, August MDC, and the JJA mean precipitation values.

4.2 Historical Simulations

Simulations of the August mean daily maximum temperatures (not shown) provided variable results: R^2 values range from 0.37 to 0.83 for the evaluation time period, depending on the station. JJA precipitation simulations (Figure 4) show slightly poorer skill as compared to temperature; R^2 values computed on data not used in the calibration of the BCSD method (after 1990) range from 0.31 (Cranbrook) to 0.77 (Penticton). Accuracy of the downscaled August MDC is also shown in Figure 4. R^2 values computed on data after 1990 range from 0.36 (Blue River) to 0.72 (Kelowna). All correlations are statistically significant at the 5% level. Importantly, the extreme MDC values observed at Kelowna and Penticton in 2003 (which was an extreme fire season within the region) are well simulated.

4.3 Future Projections

Figure 5 shows examples of temperature, precipitation and MDC projections for two different GCMs, the CSIRO and CNRM models, using the A2 emission scenario. These cases were chosen to provide extreme examples of future MDC anomalies. Both models produce significant temperature increases of over four degrees by the 2080s. However, there is substantial divergence between the two precipitation projections; the CNRM model projects a decrease in precipitation while the opposite is true for the CSIRO model. The resulting MDC projections indicate that increases

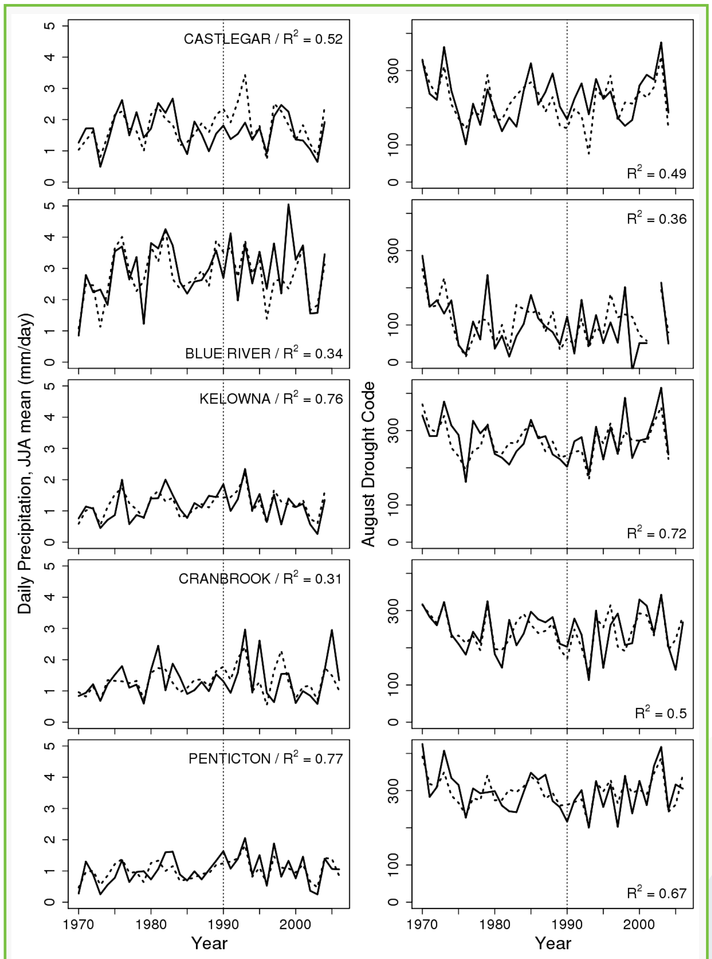

Figure 4: Simulation (dashed line) of observations (solid line) of JJA mean daily maximum precipitation (left column) and August MDC (right column) for all EC stations (rows). Simulations are based on NCEP reanalysis data downscaled with BCSD. Correlations are computed on data outside of the calibration period (after 1990 - vertical dashed line) and associated R^2 values are provided in each figure.

in precipitation are balanced by temperature increases resulting in higher future MDC values in both cases, although the CSIRO anomaly is not statistically significant at the 5% significance level. It is important to note that the historical variability of precipitation and MDC is large compared to the future anomalies.

Moving beyond this example, Figure 6 and Figure 7 provide projected future values of JJA precipitation and August MDC for all stations, models and scenarios. Observed historical medians and variability are included for comparison. Absolute values of JJA precipitation projections show little preference to either more or less precipitation versus the median of the historical values and are within the range of historical variability, especially in the 2050s. However, the consistent warming seen in all models and stations results in increasing MDC versus the historical median in almost all cases (see Figure 7). However, the ensemble spread is quite large. The difference in the mean future (2041-2070 or 2071-2100) MDC values versus the historical (1961-1990) values for the same GCM was analyzed using the two-sample t-tests. Results indicate that of the 90 different projections (i.e., 5 stations × 3 emissions scenarios × 6 GCMs), 38 cases

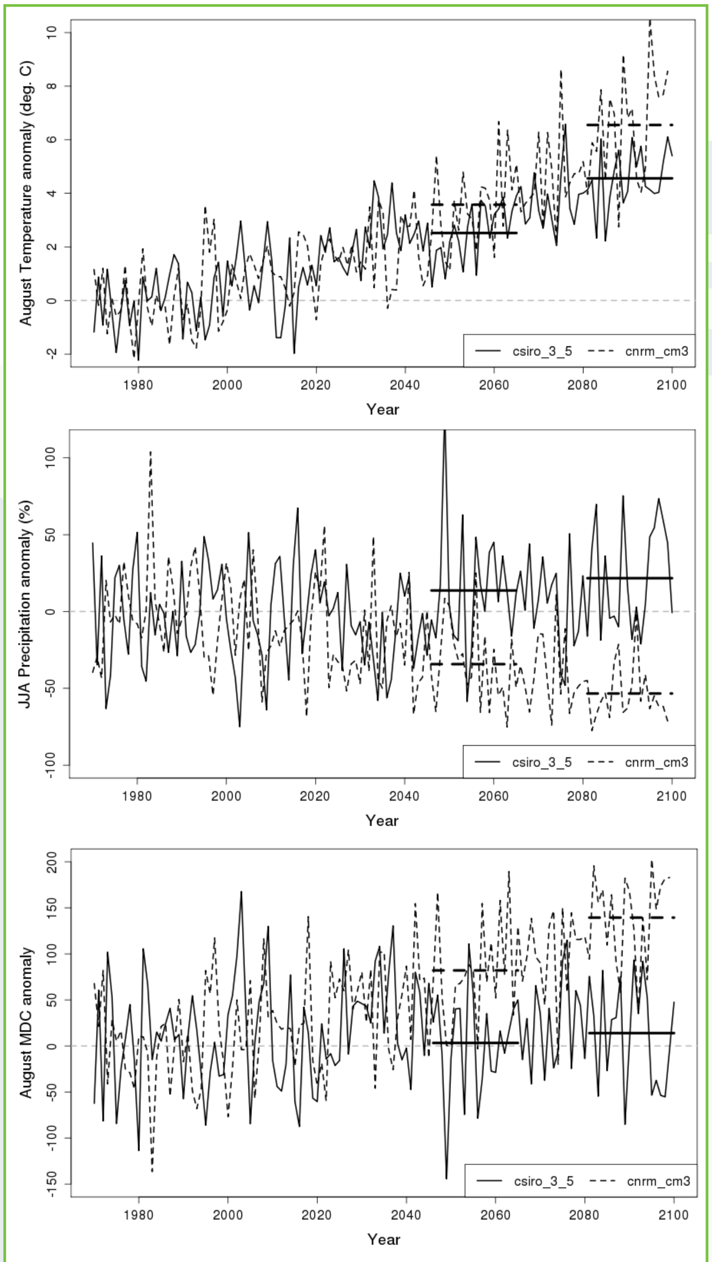

Figure 5: Example future projections at Castlegar for: August mean of daily maximum temperature (top), JJA precipitation (middle), and August MDC (bottom) from both the CSIRO3.5 and CNRM GCMs. The A2 emission scenario was used in both cases. Values are given as anomalies from the historical mean. The two models were chosen to provide extreme examples of future changes in MDC.

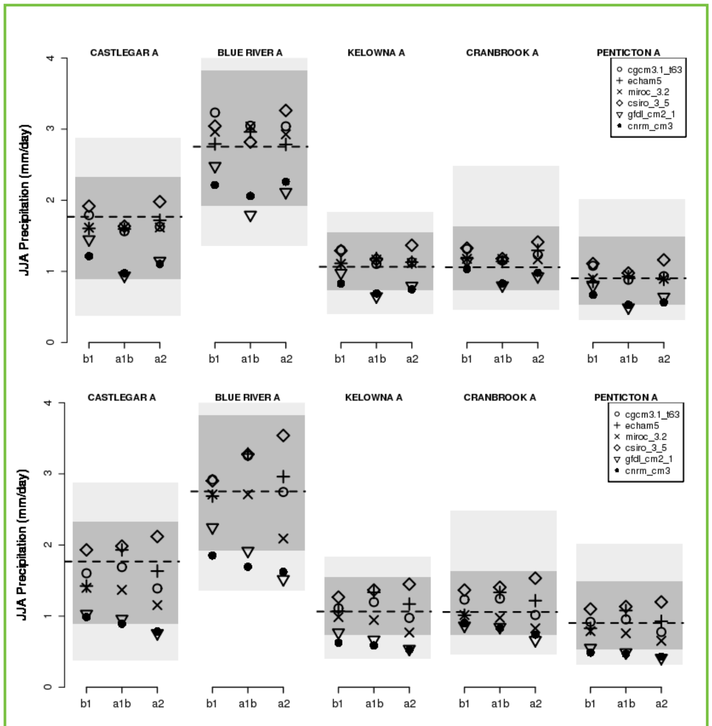

Figure 6: Projected levels of JJA average daily precipitation for all stations, models and scenarios in the 2050s (top) and 2080s (bottom). Percentiles of historical observations are indicated by the shaded boxes: The light grey box extends to the 10th and 90th percentiles, the dark grey box extends to the 25th and 75th percentile while the dashed line indicates the historical median.

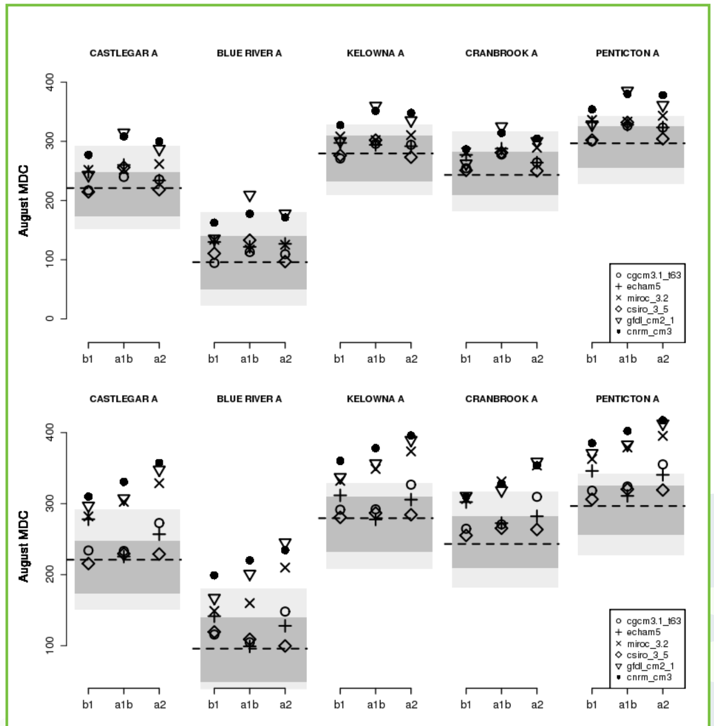

Figure 7: Same as Figure 6 but for August MDC.

show statistically significant changes in the MDC at the 5% significance level for the 2050s, while for the 2080s 49 cases show statistically significant changes.

The CSIRO, ECHAM and CGCM models, which project significant increases in precipitation, result in the smallest future changes in MDC, many of which are insignificant, while the driest models (GFDL and CNRM) generally produced the most extreme anomalies, some of which suggest significant shifts in fire activity. For example, at the drier Okanagan sites the largest future increases place mean MDC values within the "extreme" range of over 400. These levels are well outside the typical historical range within that region: in 2003, which was an extreme fire year for southeast BC, the observed August MDC was 418 and 415 for Penticton and Kelowna, respectively. As well, average projections for the 2080s place Castlegar within the historical fire weather regime of Kelowna and Penticton. The historical average AAB value of the Kelowna and Penticton watershed is 86% larger than that of the Castlegar watershed (using data from 1950 to 2009).

We found that MDC anomalies were most strongly influenced by future changes in summer precipitation. Regressing JJA precipitation anomalies against anomalies of August MDC resulted in an R^2 value of 0.88, while for August maximum daily temperature the value was 0.48. This strong relationship between changes in precipitation and the MDC is evident in Figure 8. Here we have provided a scatter plot of anomalies for all periods, scenarios, models and stations. MDC anomalies vary greatly along a given line of constant temperature anomaly depending on the precipitation projection. For instance, cases with a temperature anomaly of 5 degrees show a large range of MDC anomalies, from no significant change to increases of over 100. In contrast, differences in MDC anomalies are not nearly as large among cases with similar precipitation anomalies.

5 DISCUSSION

5.1 MDC as predictor of Annual Area Burned

We have shown that in general the August MDC correlates strongly with the log of AAB, and performs better than both of its input variables, precipitation and daily maximum temperature, in the vast majority of cases. The usefulness of the MDC as a metric for AAB is most pronounced at the regional scale (the entire southeast region of BC) where it shows signifi-

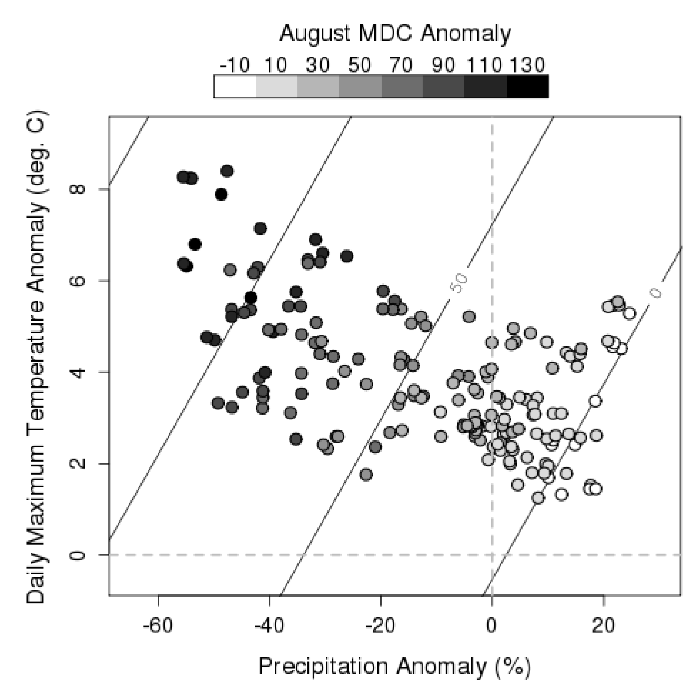

Figure 8: August average daily maximum temperature anomalies plotted against JJA average of daily precipitation anomalies given as a percentage. August MDC anomalies are indicated by the shading of the points. Contour lines indicate the plane fitted to the data using a 2-dimensional regression. The interval of the contour lines is 50.

cantly higher correlations than temperature. At this regional scale, major fire years often correspond with widespread drought conditions created by persistent blocking-highs (Heyerdahl et al. 2008). These regional droughts are more readily captured by the MDC than by temperature alone. However, at the local scale of individual catchments precipitation is a poor predictor and the temperature correlations are comparable to that of the MDC. An explanation of this is that, at the local scale, both precipitation and fire activity are much noisier due to small-scale weather process (e.g., thunderstorms, orographic precipitation), variability in the efficacy of fire management, and the general stochastic nature that wildfires exhibit at the landscape scale. This variability will partially mask the regional drought signal, decreasing correlations values.

The poor MDC correlation at the wettest and coolest site, Blue River, stands out and may be explained by the region's fire regime. The area surrounding this station falls within the "wet-belt" region where enhanced orographic precipitation maintains a low-frequency, high severity fire regime. Consequently, fire activity within the region, which is relatively low (see Figure 3), does not contain a clear climate signal. Only rarely is there a drought severe enough to cause significant burning in this area, and then the return period of such events may be much longer than the length of the fire dataset used here. Similar results have been found in Washington and Oregon, where burn amounts within the wetter region of the Cascade Mountains have shown poorer correlations with climate variables than in drier, forested areas (Littell et al. 2009). Yet, this does not explain why the two driest stations, Kelowna and Penticton, had poorer correlations than Castlegar and Cranbrook. Given that the region around Kelowna and Penticton has the highest density of human-caused fire starts within our study region (Magnussen and Taylor, 2012), it is possible that human-related factors, including enhanced suppression-activity, play a larger role there.

However, considering the other confounding factors that control wildfire activity, including fuel type and availability, human activity and fire suppression, and wildfire history, the correlations found here are noteworthy and comparable to results from other studies. Meyn et al. (2010a) regressed the log of AAB against the Aridity Index (a metric of drought severity) for specific biogeoclimatic zones of BC. Their largest R^2 value was 0.5. Le Goff et al. (2009) used a variety of FWI indices and meteorological variables to predict the log of AAB within a 15 000 km^2 boreal region of Quebec. Using multi-variable linear regression, their best model had an R^2 value of 0.36. Using a similar boreal region spanning the Ontario-Quebec border, Bergeron et al. (2010) applied a non-linear regression technique, Multivariate Adaptive Regression Splines (MARS), and weather interpolation to the prediction of AAB with the August MDC as the single predictor. Their AAB model had an R^2 value of 0.42. Balshi et al. (2009) also used MARS and the July MDC calculated from the NCEP Reanalysis 1 product to predict AAB at grid points throughout Canada. The average R^2 of their models across all grid points was 0.53. Littell et al. (2009) used linear regression to connect climate variables to the log of AAB for ecoprovinces throughout the western United States. Their optimized multivariate regressions had an average R^2 value of 0.64. Their North Rockies ecoprovince, is similar to our study area, had an R^2 value of 0.74. Considering their more sophisticated approach this compares favourably to our R^2 value of 0.68 for the regional AAB (see Table 6).

These favourable comparisons demonstrate that using inter-station interpolation (as in Bergeron et al. 2010) or gridded reanalysis products (as in Balshi et al. 2009) to fire weather in BC may not be worth the increased uncertainties inherent in applying such techniques to regions of complex terrain. An average across a handful of sites within the region correlates strongly with the regional AAB value, considering all of the other confounding factors that are not simulated by the MDC. The large spatial covariance structure of surface temperatures mentioned above helps explain the ability of a handful of stations to predict fire severity over a large region.

Finally, our results suggest that if we are interested in seasonal severity of wildfire activity and its variability from year to year, we can avoid the use of daily data, which are difficult to acquire, process, and simulate (especially in the case of surface wind speeds), with little or no reduction in predictive skill. As well, these results also suggest that information on the start of the fire season is less important when predicting AAB; The MDC, which was calculated using a constant start date, had stronger correlations than the operational DC, which uses variable fire season start dates.

5.2 Historical simulations

Much of the reduction in MDC reproduction skill was a consequence of poor precipitation results. This reduction in accuracy as compared to temperatures is likely due in part to the inability of the NCEP Reanalysis product to resolve local and mesoscale dynamics such as convective activity and orographic lift that can play a significant role in determining precipitation rates for a specific location. Another likely factor is that while temperature observations are directly assimilated into the NCEP reanalysis product, precipitation is not; precipitation output is not constrained in the same way by observations as temperature (Kalnay et al. 1996). This product is known to have a spurious pattern in the precipitation fields in mid to high latitudes, most notably in winter, poleward of about 50 degrees (Sheffield et al., 2004).

Additionally, sampling error may also be an issue. The 20 years of data used to train the BCSD algorithm (1970 to 1990) may not be large enough to properly characterize the observed probability distributions. In the BCSD algorithm, cumulative distributions of precipitation or temperature are approximated by distribution functions, which are then used to extrapolate when predictor values fall outside the historical range. Consequently, extreme cases in the evaluation period may not be accurately simulated. This is especially true for precipitation (Wood et al. 2004). Examples of this are seen in the precipitation reproductions at Blue River in 1999 and Cranbrook in 1995 (Figure 4). These poor reproduction years have a significant impact on the final correlation values. Stations with less variability such as Kelowna and Penticton are less likely to be subject to this sampling error, leading to higher reproduction skill. These errors may be reduced by lengthening the training period, but this presents a trade-off as it reduces the number of stations with a sufficient record length.

5.3 Future Projections

A significant result of this study is the wide range of MDC projections and the strong sensitivity of those projections to future changes in precipitation. As previously mentioned, there is a large spread in precipitation projections among different GCMs and this is especially true for southeast BC. This ensemble spread is due to a number of sources of uncertainty that are to a large degree unavoidable. Firstly, there is the inherent non-predictable behaviour of the chaotic, non-linear climate system, which will lead to a spread in precipitation projections even within a single GCM, especially for the first half of the 21st century (Deser et al. 2012). Secondly, there are uncertainties in future emission levels of greenhouse gases and aerosols that are dependent on complex social, political, and economic factors. Thirdly, GCMs are required to parameterize most precipitation-relevant processes as they are too small to be resolved. Differences in parameterization schemes will lead to different responses to the same climate forcings. These issues are compounded by the fact that our downscaling technique uses information from single grid cells only, which leads to sampling error.

Figure 2 demonstrates that three models commonly used in previous studies of Canadian wildfire projections, the first two generations of the CGCM model as well as the HadCM3 model, do not represent the entire range of CMIP3 GCMs, especially if only one or two of the models are used. For instance, none of the three models project increases in precipitation. A number of studies have used a larger ensemble of GCMS to produce projections of fire weather severity, which also demonstrate the sensitivity of fire weather projections to GCM choice. McCoy and Burn (2005) utilized six GCMs and found that while some models produced no significant changes in fire weather severity, others did show statistically significant changes. Bergeron et al. (2010) used a suite of seven GCMs (three of which were common with the suite of GCMs used here) to generate MDC projections within the eastern boreal region. Their results agree broadly with ours: median increases in the August MDC of 35 and 55 for the 2050's and 2080's, respectively, with a broad range of changes (many of which were statistically insignificant), depending on the scenario and model. However, their range of MDC projections is slightly smaller than ours, with fewer decreases in MDC and smaller maximum increases. This is primarily due to the larger spread in our precipitation projections, which had more extreme decreases.

6 CONCLUSIONS

We tested the usefulness of the Monthly Drought Code (MDC) as a metric for seasonal fire activity and used a suite of global climate models (GCMs), combined with the Bias Correction Spatial Disaggregation (BCSD) statistical downscaling technique to produce future projections of the MDC for five stations throughout southeast British Columbia.

We assessed the usefulness of the MDC to predict wildfire severity by regressing MDC time series against AAB. In most cases correlations compared favourably to the results of previous studies (which often used more complicated statistical models), the skill of more complex operational fire weather indices and the MDC input variables, though the sample size used here is generally smaller that the sample sizes used in comparable studies. The results are also reasonable considering the other confounding non-climate factors that influence wildfire activity. This demonstrates that the MDC provides a simple but effective metric for simulating wildfire severity that avoids the difficulties in acquiring and simulating daily data, surface winds, and fire season start dates.

This is especially true at the regional scale of the entire southeast BC area. We found that a regional MDC, calculated as an average over a small number of long-term, valley bottom stations correlated strongly with wildfire activity summed across our entire region of complex topography with an area on the order of 100,000 km^2. This is partially due to the use of monthly means; at this timescale much of the spatial variability in temperature and precipitation are averaged out. As well, this regional average more accurately reflects the large-scale synoptic conditions that lead to extreme drought and fire years. Therefore, using high-quality station data would allow one to avoid either interpolating weather data across a complex region or using regional climate model output, both of which come with a variety of errors and uncertainties.

With our downscaling technique (BCSD) we were able to simulate the historical variability in the MDC reasonably well, especially for the drier stations as evaluated by downscaling NCEP Reanalysis. The main limitation of BCSD is difficulty reproducing precipitation in regions with strong orographic uplift when only short records are available for calibration.

We developed projections of MDC at all five stations using six GCMs and three emission scenarios. The large majority of projections show increases. However, there was a significant spread in future MDC levels that range from insignificant increase in fire weather severity to increase that suggest major shifts in fire frequency. The wide range of MDC projections is primarily due to the large spread in precipitation projections across our ensemble of GCMs, many of which showed increases in precipitation that largely compensated for increases in temperature.

The results of this study suggest that the technique developed here could be useful for regions throughout North America, especially for regions where wildfire activity is moisture limited and has ample fuel supplies. Indeed, our region, which has a relatively low density of quality long-term stations, and relatively complex topography and climatological gradients, has provided a stringent test. The MDC can be easily calculated from readily available climate data at stations throughout North America and can be used as a reliable metric for wildfire activity, especially if one uses multiple stations within a region and is concerned with wildfire activity averaged over regions on the order of 100 000 km^2 or greater. Also, at these regional scales the MDC represents a significantly improved wildfire metric compared to its input variables. However, the unavoidable uncertainties that come with future precipitation projections, coupled with the strong sensitivity of wildfire activity to these changes, suggests significant uncertainties in future wildfire activity.

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