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ORIGINAL ARTICLE

Precipitation-driven decrease in wildfires in British Columbia

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Abstract Trends of summer precipitation and summer temperature and their influence on trends in summer drought and area burned in British Columbia (BC) were investigated for the period 1920–2000. The complexity imposed by topography was taken into account by incorporating high spatial resolution climate and fire data. Considerable regional variation in trends and in climate–fire relationships was observed. A weak but significant increase in summer temperature was detected in north-eastern and coastal BC, whereas summer precipitation increased significantly in all regions—by up to 45.9 %. A significant decrease in province-wide area burned and at the level of sub-units was strongly related to increasing precipitation, more so than to changing temperature or drought severity. A stronger dependence of area burned on precipitation, a variable difficult to predict, implies that projected changes in future area burned in this region may yield higher uncertainties than in regions where temperature is predominantly the limiting factor for fire activity. We argue that analyses of fire–climate relationships must be undertaken at a sufficiently high resolution such that spatial variability in limiting factors on area burned like precipitation, temperature, and drought is captured within units.

Keywords Fire · Aridity index · Self-calibrating Palmer Drought Severity Index · Regional climate change · Summer temperature · Summer precipitation · Summer drought · Trends

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Introduction

Understanding the historical relationships between precipitation, temperature, drought, and area burned can provide important insights into the potential impacts of future climate change on wildfires. British Columbia, Canada's western-most province, encompasses complex topography that causes a substantial variety of ecosystems and climates to occur in close proximity—both horizontally and vertically. This complex environmental setting is at the source of important spatial variations in the area burned in this province (Meyn et al. 2010a, b). For instance, the recurrence intervals of large fires (i.e., the average amount of time between fires of 10 km^2 or larger that occur in an area of 10,000 km^2) decrease in magnitude by an order of three (from 28–36 years between events to 13–18 years) as one moves from the coast to higher elevations and in the

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interior of the mountain ranges (e.g., Jiang et al. 2009). Regional variations in temporal trends, both in directions and levels, are also reported in the literature through the analysis of paleofire records spanning up to the last 12,000 years (Bergeron et al. 2004; Gavin et al. 2007). On short-terms, however, contemporary fire statistics indicate that fire activity has been steadily decreasing in British Columbia during the past 50 years (Taylor et al. 2006), and a recent study by Meyn et al. (2010b) pinpoints the decreasing dryness as a contributing factor to this trend.

Spatial and temporal variations in the area burned in British Columbia are likely related to the degree to which precipitation and temperature limit fire spread (other effects like the amount and quality of fuel, wind velocity, and ignition limitations being excluded). A lack of moisture or an excessive evaporative demand driven by above normal temperatures, or both occurring simultaneously, are facilitators for large burned areas (Girardin and Wotton 2009). In the course of increasing our understanding of fire–climate relationships, it is relevant to determine whether temperature or precipitation is most limiting to contemporary dryness and wildfire risk in British Columbia, and how each has contributed to the emergence of trends in fire activity across the province. It is equally relevant that this knowledge be acquired at spatial resolutions and extents and with temporal depths that are both ecologically significant and important for management and adaptation strategies.

In this study, we investigate in a spatially explicit manner whether the observed summer wetting and fire trends in British Columbia during 1920–2000 (Meyn et al. 2010b) are triggered by changes in temperature or precipitation. We identify trends in summer temperature and precipitation at regional scale based on fine-scale resolution data, investigate their contribution to the summer drought and fire activity trends, and determine whether these relationships differ regionally.

Materials and methods

Study area

The study area is Canada's western-most province, British Columbia (BC), located between ~48° and 60°N of latitude and encompassing ~950,000 km^2 in land area. Except for the boreal plains in the northeast, BC is dominated by western North America's north–south-oriented Cordilleran mountain system. Climatic conditions in the province are determined primarily by a combination of distance to the Pacific Ocean, topography and latitude. The Coast Mountains constitute a barrier to moisture-laden winds from the Pacific Ocean; the Rocky Mountains limit the westward flow of cold continental arctic air masses from central Canada. This creates a strong west–east gradient in precipitation and continentality, and a strong lee effect. It is reported by previous studies that both summer precipitation and temperature increased significantly during the twentieth century across BC (Vincent and Mekis 2009; Zhang et al. 2000; Mote 2003; Vincent et al. 2007). However, this knowledge is based on low spatial resolution data (5° latitude × 10° longitude in Easterling et al. 2000; three climate regions in Mote 2003, and Vincent et al. 2007; a 50-km grid in Zhang et al. 2000; a 4-km grid in Mbogga et al. 2009), or on individual climate stations (Vincent et al. 2007; Vincent and Mekis 2009). Analysis based on high spatial resolution data covering the entire BC province is still missing.

The study area comprises a variety of ecosystems, from temperate rainforests on the Pacific coast over dry grasslands in the driest valleys of southern interior BC to boreal forests in the northeast and alpine meadows at high elevations that result from these diverse climatic and orographic conditions. We subdivided the study area (BC) into 16 subregions or zones, based on the Biogeoclimatic Ecosystem Classification System (BEC; Meidinger and Pojar 1991) (Table 1; Fig. 1). Each BEC zone represents a landscape type with a broadly homogeneous natural vegetation and macroclimate. In BC, these zones often fall within narrow elevational bands (see Fig. 1), and use of high spatial resolution data is necessary in order to represent their temperature, precipitation, drought and area burned. Our analysis assumes that landscapes classed as a particular BEC zone, with its broadly homogeneous natural vegetation and climate, are relatively homogeneous with respect to fire regime, drought, precipitation and temperature.

BEC system and landcover data

We used landcover data that are based on an intersection of the biogeoclimatic classification (BEC) with a provincial base map that delineates three classes: land, freshwater and permanent ice or snow (BC Ministry of Forests and Range 2006b). Land, including urban areas and cropland, was considered to be the flammable portion of a BEC zone. Detailed information on the biogeoclimatic classification system can be found in Meidinger and Pojar (1991) and at http://www.for.gov.bc.ca/HRE/becweb/ (accessed 20 April 2010).

Version 6 of the vector geographic information system (GIS) layer of the Biogeoclimatic Classification Subzone/Variant Mapping was used for our analyses (BC Ministry of Forests and Range 2006a).

Temperature data, precipitation data and drought indices

Monthly mean temperature and monthly precipitation data with a spatial resolution of 400 m were generated for the

Table 1 Biogeoclimatic Ecosystem Classification (BEC) zones of British Columbia (BC)

Biogeoclimatic zone		Total size in BC		NV (%)	$PDSI_s$	P_s (mm)	T_s (°C)
Abbreviation	Full name	km^2	%				
BAFA	Boreal Altai Fescue Alpine	75,039	7.9	10.9	−0.18	260	8.0
BG	Bunchgrass	2,834	0.3	10.0	−0.23	105	16.4
BWBS	Boreal White and Black Spruce	156,838	16.5	2.3	−0.03	200	13.1
CDF	Coastal Douglas-fir	2,597	0.3	1.6	−0.18	99	16.2
CMA	Coastal Mountain-heather Alpine	43,547	4.6	44.4	−0.32	361	9.2
CWH	Coastal Western Hemlock	107,717	11.4	3.3	−0.26	312	13.5
ESSF	Engelmann Spruce-Subalpine Fir	170,353	18.0	1.0	−0.05	238	10.4
ICH	Interior Cedar-Hemlock	55,059	5.8	5.8	−0.05	198	13.5
IDF	Interior Douglas-fir	44,291	4.7	3.2	0.01	131	14.0
IMA	Interior Mountain-heather Alpine	16,082	1.7	32.9	−0.16	269	7.7
MH	Mountain Hemlock	35,514	3.7	2.9	−0.27	350	11.0
MS	Montane Spruce	28,266	3.0	0.8	0.08	158	11.6
PP	Ponderosa Pine	3,729	0.4	7.4	−0.09	97	16.6
SBPS	Sub-Boreal Pine–Spruce	23,368	2.5	2.5	0.11	147	11.6
SBS	Sub-Boreal Spruce	103,105	10.9	6.6	0.15	173	12.6
SWB	Spruce–Willow–Birch	79,761	8.4	1.3	−0.05	223	9.7

NV non-vegetated, percentage of land covered by permanent ice and snow or freshwater excluded from the analysis

$PDSI_s$ mean summer self-calibrated Palmer Drought Severity Index (scPDSI) 1920–2000

P_s mean summer precipitation

T_s mean summer temperature

period 1920–2000 using the scale-free climate model, ClimateBC (Hamann and Wang 2005; Wang et al. 2006). This model combines historical monthly climate variability data (CRU TS 2.1 data from Mitchell and Jones 2005) with downscaled PRISM monthly climate normal data (PRISM; Daly et al. 2000, 2002). CRU data are interpolated anomalies from climate normals (Mitchell and Jones 2005). These are less vulnerable to missing values for station data than interpolated absolute climate values are, because they can be forced to approach climate normals (e.g., a zero anomaly) where values are missing (Mitchell and Jones 2005; Mbogga et al. 2009). This can be better dealt with in biological (Mbogga et al. 2009) and fire–climate-relationship and trend analyses.

PRISM monthly climate normal data are computed based on a statistical regression model called parameter-elevation regressions on an independent slopes model (PRISM; Daly et al. 2002). The model includes expert knowledge on the spatial patterns of climate and their relationships with geographic features in the form of algorithms (Daly et al. 2002). It links statistical methods with human expertise using knowledge-based system (KBS) technology as its basic structure (Daly et al. 2002). PRISM contains a digital elevation model, point station data, other spatial datasets, a knowledge base and human-expert parameterization (Daly et al. 2002). ClimateBC monthly temperature and precipitation data were used to calculate mean summer (i.e., June to August) temperature and precipitation for each BEC zone and for the province of BC overall for the period 1920–2000.

Two drought indices, the self-calibrating Palmer Drought Severity Index (scPDSI) of Wells et al. (2004) and the Aridity Index (AI; United Nations Environment Programme 1992), were used. Both summer drought indices were calculated for each BEC zone using ClimateBC monthly temperature and precipitation data with a spatial resolution of 400 m for the period 1920–2000 (Meyn et al. 2010b). The scPDSI determines excesses or deficiencies of moisture availability in relation to average climate values at a specific location. It is thus standardized to local climatology. The scPDSI includes precipitation, potential and actual evapotranspiration, infiltration of water into the soil, and runoff. scPDSI values are divided into 11 classes and range from ≥ 4 (extremely wet) to ≤ -4.00 (extreme drought; Table 2). We used the formulation of Wells et al. (2004) for computation. The aridity index is defined as *P*/PET where *P* is the monthly precipitation and PET is the monthly potential evapotranspiration (both in mm). The computation of PET is based on the formulation of Thornthwaite (1948). Further details on the calculation and

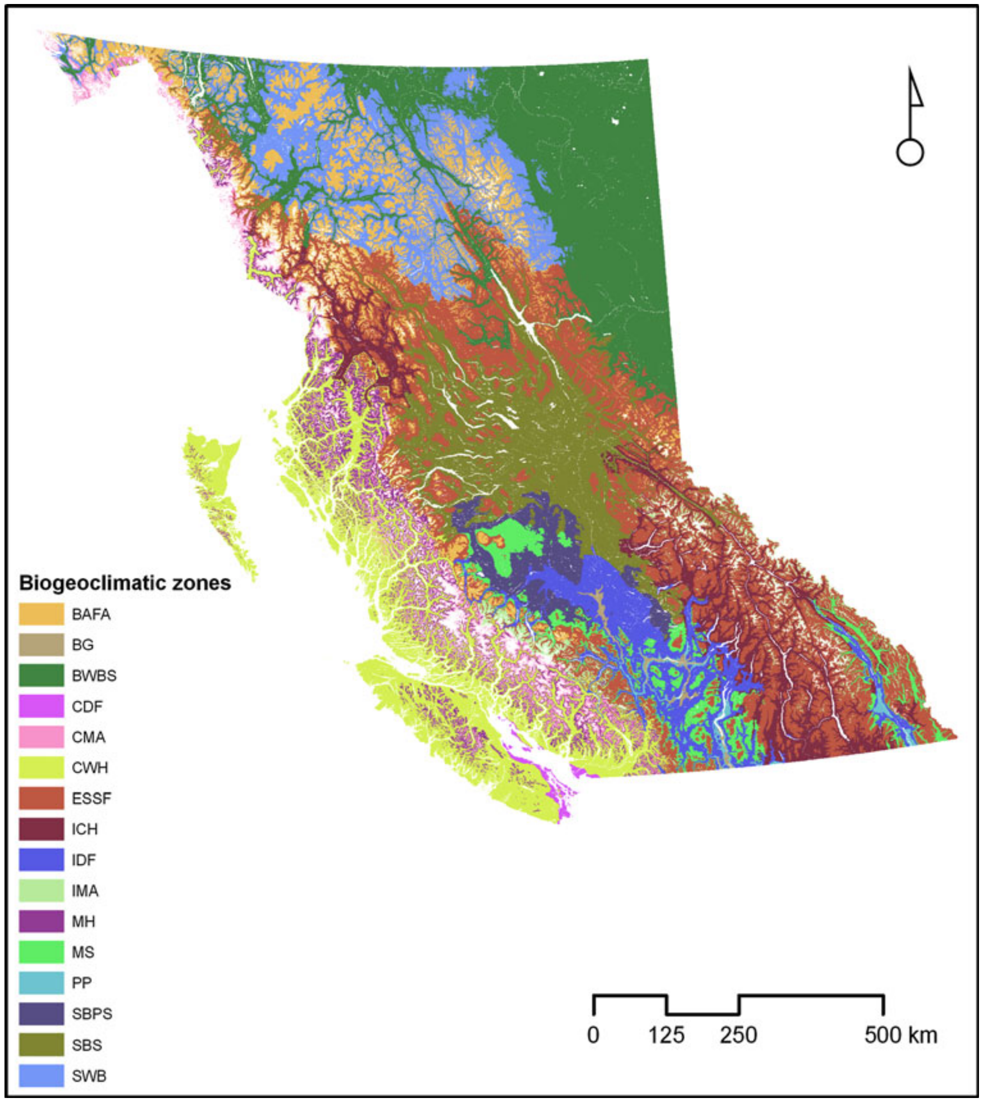

Fig. 1 Map of the biogeoclimatic zones of British Columbia, Canada. BAFA: Boreal Altai Fescue Alpine; BG: Bunchgrass; BWBS: Boreal White and Black Spruce; CDF: Coastal Douglas-fir; CMA: Coastal Mountain-heather Alpine; CWH: Coastal Western Hemlock; ESSF: Engelmann Spruce-Subalpine Fir; ICH: Interior Cedar-Hemlock; IDF: Interior Douglas-fir; IMA: Interior Mountain-heather Alpine; MH: Mountain Hemlock; MS: Montane Spruce; PP: Ponderosa Pine; SBPS: Sub-Boreal Pine-Spruce; SBS: Sub-Boreal Spruce; SWB: Spruce–Willow–Birch. Zones are according to version 6 of the vector geographic information system (GIS) layer of the Biogeoclimatic Subzone/Variant Mapping (BC Ministry of Forests and Range 2006a). *White areas* represent non-flammable areas (permanent ice and snow, freshwater), which were excluded from the analysis

input data for these two indices are given by Meyn et al. (2010b).

Fire data

Fire data used in this study are from a digital, spatially explicit fire database constructed from administrative fire records, forest inventories, and remote-sensing data by the Canadian Forest Service and the BC Ministry of Forests and Range Research Branch (Taylor and Thandi 2003). The database includes 16,559 fires of size greater than 20 ha reported between 1920 and 2000. Fires that occurred in national parks and within a 64-km-wide strip of land on each side of the Canadian Pacific Railway between the towns Field and Port Moody before 1930 were excluded (Taylor and Thandi 2003). In this study, the annual proportion of flammable area burned in the province of BC and in each of its 16 BEC zones was used (Meyn et al. 2010b).

Statistical analyses

Detection of trends in summer precipitation and temperature during 1920–2000 was conducted using least-squares linear regressions. The coefficient of determination (R^2) was used as a measure for the goodness-of-fit, whereas the regression coefficient was used to estimate the trend's strength. Pearson correlation analysis was used to analyze the relationship between summer temperature, summer precipitation, summer drought, and area burned for each BEC zone. Pearson correlation and linear regression analyses assume independent (random) data that also qualify for the normality assumption. Thus, all time series were tested for positive serial correlation and for normality. For

Table 2 Linear trends of mean summer temperature and summer precipitation in British Columbia (BC) and its Biogeoclimatic Ecosystem Classification (BEC) zones, from 1920 to 2000, based on linear regression analysis

Biogeoclimatic zone	Mean summer temperature			Summer precipitation			
	Adjusted R^2	Increase ±95 % confidence interval (°C)	Significance (P)	Adjusted R^2	Relative increase ±95 % confidence interval (%)	Absolute increase ±95 % confidence interval (mm)	Significance (P)
British Columbia[a]	0.03	0.45 ± 0.28	$P < 0.10$	0.18	31.8 ± 8.6	63 ± 17	***
BAFA	0.06	0.67 ± 0.31	*	0.16	32.4 ± 9.3	72 ± 21	***
BG	0.00	0.02 ± 0.37	n.s.	0.05	29.2 ± 14.4	27 ± 13	*
BWBS[a]	0.04	0.53 ± 0.28	*	0.14	36.6 ± 11.1	62 ± 19	***
CDF	0.00	0.04 ± 0.28	n.s.	0.04	29.8 ± 16.6	26 ± 14	*
CMA	0.03	0.47 ± 0.29	$P < 0.10$	0.11	25.1 ± 9.0	81 ± 29	**
CWH	0.04	0.48 ± 0.28	*	0.06	22.7 ± 10.6	64 ± 30	**
ESSF	0.01	0.37 ± 0.30	n.s.	0.17	34.3 ± 9.4	70 ± 19	***
ICH	0.01	0.34 ± 0.31	n.s.	0.19	39.6 ± 10.4	66 ± 17	***
IDF	0.00	0.11 ± 0.35	n.s.	0.09	34.8 ± 13.4	39 ± 15	**
IMA	0.00	0.13 ± 0.31	n.s.	0.16	35.1 ± 10.1	80 ± 23	***
MH	0.03	0.51 ± 0.30	$P < 0.10$	0.09	26.4 ± 9.9	82 ± 31	**
MS	0.00	0. 25 ± 0.33	n.s.	0.13	40.6 ± 12.8	53 ± 17	***
PP	0.00	0.32 ± 0.35	n.s.	0.11	42.4 ± 14.7	34 ± 12	**
SBPS	0.00	0. 23 ± 0.34	n.s.	0.13	45.9 ± 14.8	55 ± 18	***
SBS	0.01	0.41 ± 0.35	n.s.	0.09	30.0 ± 11.8	45 ± 18	**
SWB	0.07	0.70 ± 0.31	*	0.14	33.1 ± 10.2	63 ± 20	***

See Table 1 for definitions of biogeoclimatic zone abbreviations

n.s. not significant

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$

[a] For the mean summer temperature in BC overall and in the BWBS zone, the nonparametric Mann–Kendall trend test was also applied, as data deviate significantly from the normal distribution. Results are similar to those from linear regression analysis (positive trend, BC: $P < 0.10$; BWBS: $P < 0.05$). For summer precipitation in the BWBS zone, the nonparametric Mann–Kendall trend test was also applied, as data deviate significantly from the normal distribution. Results are similar to those from linear regression analysis (positive trend, $P < 0.001$)

data that significantly deviated from the normal distribution, the nonparametric Mann–Kendall trend test was used to test for significant trends (Mann 1945; Kendall 1970). The slope of the trends was estimated using the nonparametric Theil–Sen approach (Theil 1950; Sen 1968), and the nonparametric Spearman rank correlation analysis was used to determine relationships. For correlation analysis, the level of significance P was determined after adjusting the sample size for autocorrelation using the effective sample size as per Dawdy and Matalas (1964; 8-III, equation 8-III-45). Since some time series (scPDSI data for all BEC zones, for the aggregated statistic for BC, and area burned data for three BEC zones) show significant positive autocorrelation in lag 1, in our correlation analysis of area burned and drought, we use the P value as a measure for the goodness-of-fit since, unlike the coefficient of determination, it is corrected for autocorrelation.

Results

Trends in summer temperature

Summers in BC showed a warming trend ($P < 0.10$) during 1920–2000, as indicated by both linear regression analysis (Table 2) and the Mann–Kendall trend test (slope = 0.0055; $P = 0.068$). However, strength and significance of trends in summer temperature vary from zone to zone (Table 2; Figs. 2, 3). Summer temperature increased significantly (0.37–0.52 °C) in most parts of wind-exposed, coastal BC. In continental BC, a strong warming trend (0.53–0.70 °C) was also detected, particularly in the northeast (BAFA, BWBS, and SWB; Table 2; Fig. 2). No trend was noted for the CDF zone located in the rain shadow of Vancouver Island, and in the southeast (the montane region; Fig. 3).

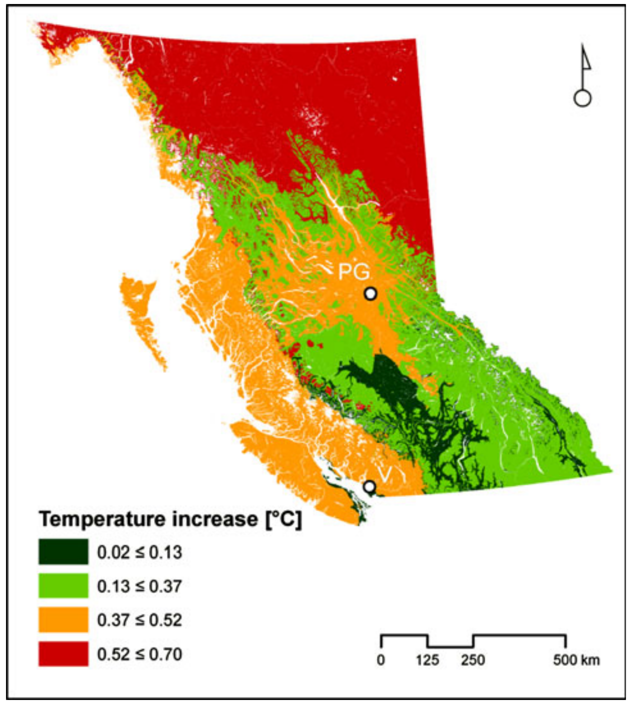

Fig. 2 Mean summer temperature increase in British Columbia's Biogeoclimatic Ecosystem Classification (BEC) zones over the period 1920–2000, based on linear least-squares regression analysis. *White areas* represent non-flammable areas (permanent ice and snow; freshwater) excluded from the analysis. Cities of Vancouver (V) and of Prince George (PG) are indicated by *circles*

Trends in summer precipitation

There was a significant increase in summer precipitation in BC overall and in each BEC zone during 1920–2000 (Fig. 4). Here, too, the significance and the strength of the trend vary between BEC zones (Table 2; Fig. 5). Linear regression analysis suggests that the absolute summer precipitation increase is strongest in the MH zone (montane elevations on the windward side of the Coast Mountains; by 82 mm over the 81-year period) and in the alpine zones (CMA, IMA, BAFA; by 72–81 mm over the period), and weakest in the driest valleys of BC's southern interior (BG, PP; by 27–34 mm) and on the lee coast of Vancouver Island (CDF; by 26 mm; Table 2).

Because summer precipitation varies considerably between the BEC zones, the picture differs when looking at the relative precipitation increase. The latter ranges from 22.7 % over 1920–2000 in windward coastal BC (CWH zone) to 45.9 % in the Sub-boreal Pine–Spruce (SBPS) zone in the lee of the Coast Mountains (Table 2; Fig. 4). Overall, the relative increase in summer precipitation is largest in northeastern BC (BWBS zone) and in the southern two-thirds of interior BC except for the vast interior plateau in central BC (SBS) and the driest valleys in southern interior BC (BG). The relative increase is lowest in windward coastal BC (Fig. 4). The positive trend is relatively steady over time: only the 1960s exhibit drier years in the interior zones (BG, ESSF, ICH, IDF, IMA, MS, PP, SBPS; Fig. 6).

Correlation between summer temperature and summer precipitation

For the province overall and for 13 out of the 16 BEC zones, lower summer temperatures are associated with higher summer precipitation (Table 3). The relationship is strongest in southeastern BC (montane region) and in the small CDF zone located in Vancouver Island's rain shadow, whereas it is weakest in the northern interior (BAFA and SWB zones) and at alpine elevations in coastal BC (CMA zone; beginning at 1,600 m in the south, descending

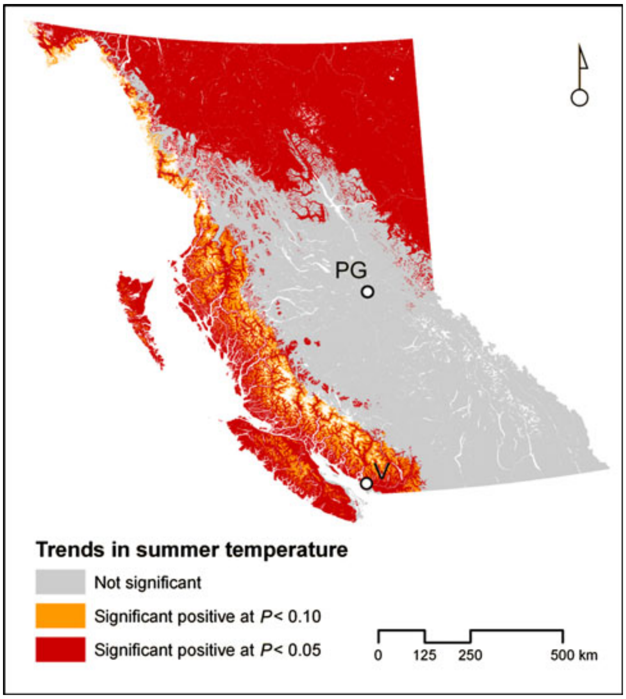

Fig. 3 Significance of summer temperature increase in British Columbia's Biogeoclimatic Ecosystem Classification (BEC) zones, from 1920 to 2000, based on linear least-squares regression analysis. For the BWBS zone (located in northeastern British Columbia), where summer temperature significantly deviates from the normal distribution, the nonparametric Mann–Kendall trend test results in the same level of significance ($P < 0.05$). *White areas* represent non-flammable areas (permanent ice and snow; freshwater) excluded from the analysis. V: City of Vancouver; PG: City of Prince George

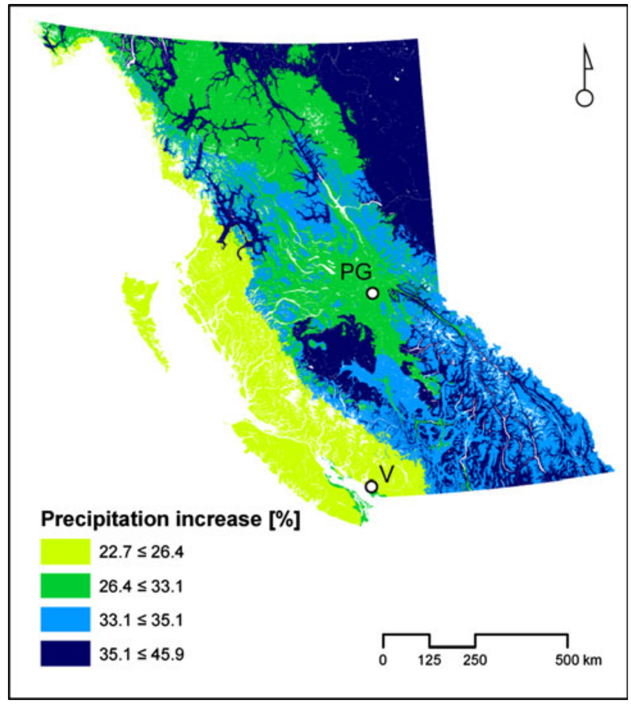

Fig. 4 Relative summer precipitation increase in British Columbia's Biogeoclimatic Ecosystem Classification (BEC) zones, 1920–2000, based on linear least-squares regression analysis. *White areas* represent non-flammable areas (permanent ice and snow; freshwater) excluded from the analysis. V: City of Vancouver; PG: City of Prince George

to 1,000 m in the north). Thus, summers in BC tend to be either warm and dry or cool and wet.

Correlation between area burned and summer drought, summer temperature, and summer precipitation

Spearman rank correlation analysis shows that area burned is related more strongly to summer precipitation than to summer temperature in BC and most BEC zones (as indicated by the level of statistical significance in Table 4). The relationship between area burned and temperature is similar in strength to that seen with precipitation, scPDSI, and AI in ICH, IMA, MH, and MS zones; in other zones, temperature is a poor predictor of area burned. Province-wide, the relationship between area burned and temperature marginally passed the significance test. Also, in all of BC area burned is related equally and in few cases more strongly to summer precipitation than to summer drought (see level of statistical significance in Table 4). Therefore, it appears from this analysis that precipitation is as suitable as the drought indices scPDSI and AI for predicting area burned in BC and BEC zones. In contrast, temperature is a poor predictor of area burned and this is valid for all of BC and for individual BEC zones.

Discussion

Trends in summer temperature and summer precipitation

Aggregated statistics for BC overall shows a tendency toward warmer summers ($P < 0.10$) during the period 1920–2000, but trend analyses for individual BEC zones reveal considerable spatial variation in the tendency's significance and strength. Analyses showed that summer temperatures significantly increased in northeastern and coastal BC. Results for coastal BC are qualitatively consistent with significant increases in summer temperature that were previously detected for six coastal BC climate stations for the period 1953–2007 (Vincent et al. 2007) and for the maritime Pacific Northwest for the period 1920–2000 (Mote 2003). The summer temperature increases in coastal and northeastern BC that were observed in the current study are also largely consistent with Zhang et al. (2000), who found a significant increase in mean summer temperatures for the period 1900–1998 for all 200-km grid cells in BC. Most of

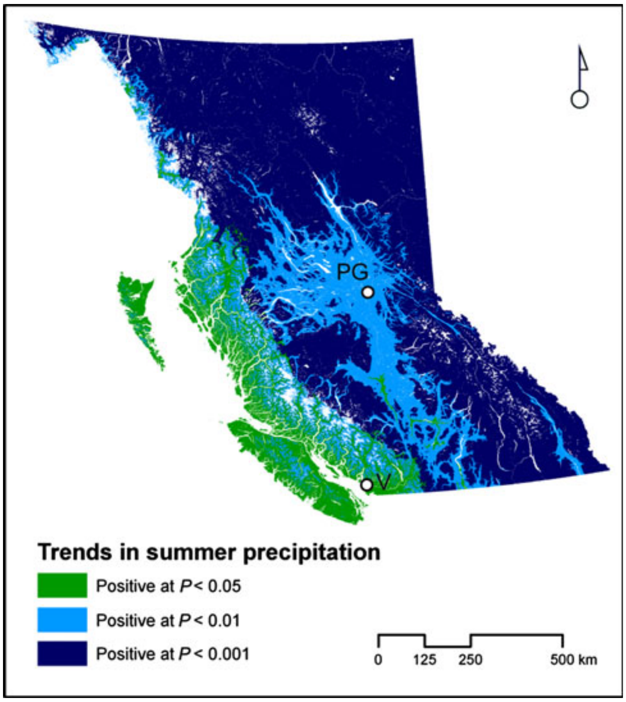

Fig. 5 Significance of linear trends in summer precipitation in British Columbia's Biogeoclimatic Ecosystem Classification zones, from 1920 to 2000. For the BWBS zone located in northeastern British Columbia, the nonparametric Mann–Kendall trend was applied because summer precipitation significantly deviated from the normal distribution and resulted in a significant positive trend ($P < 0.001$). However, linear regression analysis for this zone resulted in the same significance level (Table 2). *White areas* represent non-flammable areas (permanent ice and snow; freshwater) excluded from the analysis. V: City of Vancouver; PG: City of Prince George

the warming has occurred in daily minimum temperatures (Zhang et al. 2000). Our results cannot be compared directly to earlier results, however, due to differences in spatial resolution and in time series. As for spatial resolution, 400-m grids aggregated to BEC zones were used in the present study to account for elevational differences and other topographic differences. Vincent et al. (2007) used single climate stations; Zhang et al. (2000) used 200-km grids. As for time series, the current study refers to 1920–2000, *v*. 1953–2007 in Vincent et al. (2007), and 1900–1998 in Zhang et al. (2000).

Differences in the strength of the trend—1.07 °C per century in the maritime region of the Pacific Northwest (Mote 2003) versus the current study's maximum of 0.51 °C for 1920–2000 (or 0.63 °C, when expressed as °C per century) in coastal BC's MH zone—likely reflect slightly different seasons (July–September in Mote [2003] vs. June–August in our study), different study areas (Mote's [2003] study of the maritime Pacific Northwest includes many US climate stations), and different spatial averaging techniques. Mote (2003) calculates the trend for the maritime Pacific Northwest region by averaging station data (the majority of the stations being US stations) independently from the topographic situation of the station within the region. In contrast, the trend in our study reflects BEC zone averages that were obtained by averaging temperatures over all 400-m grid cells (whose temperatures were derived from interpolated station data that took into account topography, elevation, etc.; see section: Temperature and precipitation data). The trends in our study thus refer to BEC zones that each has broadly homogeneous macroclimate and vegetation.

We also found that summer precipitation increased significantly over the 1920–2000 period in all BEC zones. This is consistent with the work of Vincent and Mekis (2009), who found a significant increase in summer rain for the period 1930–2007 at most of the analyzed BC climate stations. It is also in agreement with Zhang et al. (2000) in regard to the increase in summer precipitation for the period 1900–1998 that is significant in nearly all 200-km grid cells that they analyzed in BC. Our results are also consistent with an increase in annual precipitation in Canadian high-latitude regions (Trenberth et al. 2007) and with a general increase in runoff and river discharge at higher latitudes (Trenberth et al. 2007). For coastal BC, the observed increase is consistent with Mote (2003). In contrast, a recent study based on observed precipitation data with 4-km spatial resolution showed that southern BC (excluding the Rocky Mountains) and northeastern BC experienced, on average, less summer precipitation during 1997–2006 compared to the 1961–1990 normal (Mbogga et al. 2009). However, as variations in precipitation occur more on interdecadal timescales (Mote 2003), decadal deviations from the linear long-term trend are to be expected. The magnitude of the increase of up to 45.9 % in summer precipitation during 1920–2000 in the BC interior (Table 2) is remarkable and consistent with Mote's (2003) results for the inland Pacific Northwest that were based on averaged station data. The trend in summer precipitation is found to be stronger than the increasing trend in summer temperature in all BEC zones and in BC overall for that period, a result consistent with the work of Zhang et al. (2000). Although trends observed in this study are consistent with results from other studies, verification with independent data, such as tree-ring data (Watson and Luckman 2004; Luckman and Wilson 2005), is warranted, especially for remote areas where few climate stations exist.

Relationship between climate and area burned

Correlation analyses revealed that drought indices for BC and BEC zones are more strongly related to change in precipitation than to change in temperature (results not shown), a result that is consistent with Guttman (1991),

Table 3 Correlation between summer temperature and summer precipitation in British Columbia (BC) and its Biogeoclimatic Ecosystem Classification (BEC) zones, from 1920 to 2000

Biogeoclimatic zone	Pearson correlation coefficient (*r*)	Significance (*P*)
British Columbia	−0.30	**
BAFA	−0.20	n.s.
BG	−0.39	***
BWBS	−0.24	*
CDF	−0.39	***
CMA	−0.22	n.s.
CWH	−0.26	*
ESSF	−0.29	**
ICH	−0.36	**
IDF	−0.38	***
IMA	−0.32	**
MH	−0.27	*
MS	−0.31	**
PP	−0.33	**
SBPS	−0.26	*
SBS	−0.33	**
SWB	−0.20	n.s.

See Table 1 for definitions of biogeoclimatic zone abbreviations

n.s. not significant

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$

who found that the impact of temperature anomalies on the Palmer Hydrologic Drought Index (an adjusted version of the PDSI; Guttman 1991) is marginal compared to the impact of precipitation anomalies. This, together with the strong precipitation trends, explains why we can observe a trend toward moister summers in BC (i.e., lower fire danger) in spite of a warming climate. It also explains why a summer wetting trend can be observed even though moister summers are related to lower temperatures. Negative correlations between summer temperature and precipitation in this study are consistent with results for western Canada for the month of July by Isaac and Stuart (1992), who investigated this relationship using daily values for the period 1951–1980. According to Trenberth and Shea (2005), negative correlations between summer temperature and precipitation imply that dry conditions promote sunshine and warmth, whereas precipitation (rain) causes evaporative cooling and its associated clouds reduce incoming radiation, thereby contributing to lower temperatures.

The observed trends in temperature are likely to have been influenced by trends in precipitation, and vice versa (Trenberth and Shea 2005). It is therefore possible that, in BC and its BEC zones, the general (global) warming trend has been buffered by the increase in precipitation that occurred during 1920–2000. A similar effect has been observed up to the 1980s for the United States. (Dai et al. 2004). On the other hand, it has been found that in BC, changes in the frequency of most synoptic-scale circulation types are related to large-scale modes of climate variability, such as the El Niño Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO) and the Pacific North American pattern during the period 1948–2003 (Stahl et al. 2006). Circulation types in turn are generally associated with distinctive patterns of precipitation and air temperature anomalies across BC in winter (Stahl et al. 2006). If this would be true for summer as well, the negative correlation between summer temperature and precipitation could be due to a common synoptic origin; that is, in summer, a circulation type that occurs mainly during increased zonal circulation would bring moist air from the Pacific Ocean that is cooler than the air over land, thereby lowering seasonal drought indices and fire danger.

Correlation analysis revealed that area burned in all BEC zones is related equally and in few cases more strongly to summer precipitation than to the drought indices (e.g., Meyn et al. 2010a). With regards to the relationship to area burned, it is surprising that drought indices, that integrate both temperature and precipitation, do not perform much better than precipitation alone. This may be because the response-times of drought indices like the scPDSI to drying and wetting are too long for recording short-term changes in weather that ultimately drive season-to-season area burned. Three days or more with less than 1.5 mm of total precipitation are sufficient to induce drying of forest fuels (Flannigan and Harrington 1988), and such events lasting up to 2 weeks have historically contributed to a record high annual area burned (Girardin et al. 2009). However, such events are unlikely to be reflected by the scPDSI. Furthermore, short-term variations that drive fire activity may also have been masked through the use of monthly mean temperatures. This may be particularly true in locations where there is a distinctly thin or absent deep duff layer. Fundamentally, it is the impact of these short-term weather variations on fire activity and fuel development that led to the creation of numerical ratings of fuel moisture in various fuel layers and several relative indices of fire behavior in Canada (Wotton 2008). However, application of these indices prior to about 1950 (e.g., Lefort et al. 2003) is challenging owing to limited records of daily weather data necessary to their computation.

Limitations and challenges

ClimateBC temperature and precipitation data for the period 1920–2000 cover the entire province of BC with a spatial resolution of 400 m. However, the area modeled and interpolated is based on a relatively small number of climate stations, especially in remote areas and at high elevations,

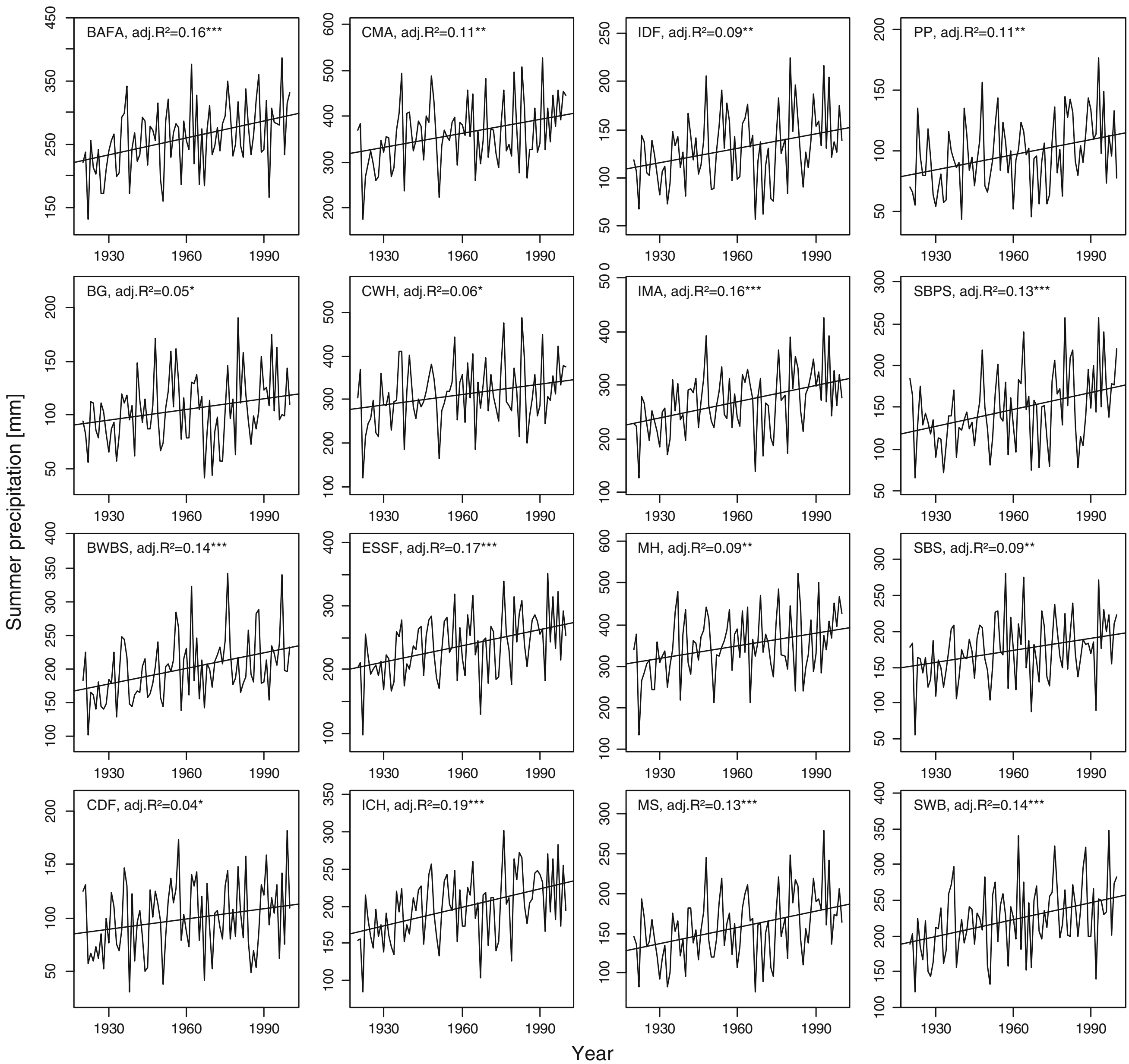

Fig. 6 Linear summer precipitation trends in British Columbia's Biogeoclimatic Ecosystem Classification (BEC) zones, 1920–2000. In the BWBS zone, summer precipitation deviates significantly from the normal distribution (Shapiro–Wilk *W* test)

and fewer climate stations existed in earlier times (Meyn et al. 2010a, b). However, historical monthly climate variability data (CRU TS 2.1 data; Mitchell and Jones 2005) are combined with downscaled monthly climate normal data (PRISM; Daly et al. 2000, 2002), the latter of which are based on a digital elevation model, point station data, other spatial datasets, a knowledge base and human-expert parametrization. ClimateBC thus provides the best and most detailed surface-weather data to completely cover BC that are currently available (Meyn et al. 2010a).

Although the fire database is exceptional in its historical and geographical coverage, it has limitations due to temporal and spatial variation in mapping methods, intensity, and accuracy that have been discussed by Meyn et al. (2010a, b). Differentiation between the impact of changes in settlement, land use, fire suppression, climate, and climate change on area burned is challenging (Podur et al. 2002; Meyn et al. 2010a, b) and likely some of the trends in burned area that we report may partly reflect these influences.

The Biogeoclimatic Ecosystem Classification (BEC) System divides BC into distinct, largely homogeneous spatial units, based on observations of similar vegetation and current climate. Our study builds on the assumption

Table 4 Correlation between annual proportion of flammable area burned ('area burned') and summer temperature, summer precipitation, summer aridity index (AI), and summer self-calibrating Palmer Drought Severity Index (scPDSI) in British Columbia (BC) and its Biogeoclimatic Ecosystem Classification (BEC) zones

Biogeoclimatic zone	Summer mean temperature		Summer precipitation		Summer aridity index (AI)		Summer scPDSI	
	Spearman rank correlation coefficient	Significance (*P*)	Spearman rank correlation coefficient	Significance (*P*)	Spearman rank correlation coefficient	Significance (*P*)	Spearman rank correlation coefficient	Significance (*P*)
British Columbia	0.24	*	−0.53	***	−0.51	***	−0.58	***
BAFA[b]	0.29	n.s.	−0.56	***	−0.51	***	−0.44	**
BG	0.11	n.s.	−0.24	*	−0.22	n.s.	−0.20	n.s.
BWBS[b]	0.15	n.s.	−0.44	***	−0.37	**	−0.44	***
CDF[a]	0.23	*	−0.38	***	−0.37	***	−0.59	***
CMA	0.34	**	−0.39	***	−0.39	***	−0.39	***
CWH	0.12	n.s.	−0.53	***	−0.5	***	−0.53	***
ESSF	0.34	**	−0.64	***	−0.65	***	−0.61	***
ICH[a]	0.36	***	−0.76	***	−0.75	***	−0.73	***
IDF	0.30	**	−0.68	***	−0.64	***	−0.54	***
IMA	0.39	***	−0.63	***	−0.60	***	−0.51	***
MH	0.47	***	−0.52	***	−0.53	***	−0.49	***
MS[a]	0.36	***	−0.72	***	−0.71	***	−0.67	***
PP	0.31	**	−0.58	***	−0.59	***	−0.34	**
SPBS	0.18	n.s.	−0.49	***	−0.45	***	−0.38	***
SBS	0.34	**	−0.59	***	−0.59	***	−0.60	***
SWB[b]	0.29	n.s.	−0.46	**	−0.43	**	−0.42	**

The period of analysis is 1920–2000. See Table 1 for definitions of biogeoclimatic zone abbreviations

n.s. not significant

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$

[a] Significant levels of the correlation between area burned and scPDSI in the CDF, ICH and MS zones were adjusted for positive autocorrelation in lag 1, based on the equivalent sample site according to Dawdy and Matalas (1964)

[b] For BAFA, BWBS and SWB, the period of complete mapping of area burned was used for analysis (BAFA: 1958–2000; BWBS: 1943–2000; SWB: 1956–2000)

that, because vegetation is an expression of current and past climate, it is possible to discriminate between these spatial units to discern regional-scale climate-related trends, such as temperature, precipitation, and drought, and area burned. A draw-back of this deductive approach may be that zoning effects may occur.

Conclusions and further research needs

Our results suggest that the trend toward moister summers in BC and its BEC zones is triggered by precipitation rather than by temperature. Consistent with this, summer precipitation was found to be a better or equally suited predictor of trends in annual area burned in BC and most of its BEC zones than derived indices of drought. As the PDSI is commonly used in climate–fire relationship investigations based on monthly or yearly data, systematic identification of the causes of the relatively weak performance of the scPDSI (and the AI) warrants further research. Considering the larger uncertainty of precipitation scenarios when compared with temperature scenarios, these results appear to be crucial for scenarios of future fire activity.

To increase our process understanding and to be able to anticipate potential impacts of regional climate change, future research should investigate the causes underlying the observed regional trends in summer precipitation and summer temperature including the frequency of synoptic circulation types and their relationship to trends in large-scale atmosphere–ocean variability. Future research should also aim at understanding the potential that increasing precipitation may have on mitigating increasing temperatures with respect to summer drought and wildfire risk. Our study shows that in regions with complex topography, aggregated statistics for the entire region hides considerable spatial variation of trends in summer temperature and precipitation, and their relationship to summer drought and area burned. Recent historical climate change information is an important source of data for estimating the spatial variation that can be expected in future regional climate change and to evaluate the reliability of spatial patterns in regional climate change projections. For example, projected regional precipitation changes for summer between 1980 and 1999 and between 2080 and 2099 for western Canada that are based on multi-model data set (MMD) A1B scenario simulations (Christensen et al. 2007) show a spatial pattern that is insufficient in resolution to account for BC's complex topography. This underscores that analyses of recent historical climate change based on high spatial resolution data are needed if estimates of the spatial variability that can be expected in future regional climate change are to be obtained.

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