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RESEARCH ARTICLE

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Key Points:
- An event attribution analysis is performed for the record-breaking wildfire season of 2017 in BC
- Anthropogenic climate change greatly increased the likelihood of extreme warm temperatures and high fire risk
- A strong anthropogenic climate change contribution is also found for the large area burned

Supporting Information:
- Supporting Information S1

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Attribution of the Influence of Human-Induced Climate Change on an Extreme Fire Season

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Abstract A record 1.2 million ha burned in British Columbia, Canada's extreme wildfire season of 2017. Key factors in this unprecedented event were the extreme warm and dry conditions that prevailed at the time, which are also reflected in extreme fire weather and behavior metrics. Using an event attribution method and a large ensemble of regional climate model simulations, we show that the risk factors affecting the event, and the area burned itself, were made substantially greater by anthropogenic climate change. We show over 95% of the probability for the observed maximum temperature anomalies is due to anthropogenic factors, that the event's high fire weather/behavior metrics were made 2–4 times more likely, and that anthropogenic climate change increased the area burned by a factor of 7–11. This profound influence of climate change on forest fire extremes in British Columbia, which is likely reflected in other regions and expected to intensify in the future, will require increasing attention in forest management, public health, and infrastructure.

Plain Language Summary A record 1.2 million ha burned in British Columbia, Canada's extreme wildfire season of 2017. Key factors in this unprecedented event were the extreme warm and dry conditions that prevailed at the time, which are also reflected in extreme fire weather and behavior metrics. To quantify the influence of human-induced climate change on this event, we compare the likelihood of the risk factors affecting the extreme fire season to an estimate of what the likelihood might have been without the human component. We find that human-induced climate change contributed greatly to the probability of the observed extreme warm temperatures, high wildfire risk, and large burned areas.

1. Introduction

A record 1.2 million ha (an area nearly the size of Connecticut) burned during the extreme 2017 wildfire season in British Columbia (BC), Canada (BC Wildfire Service, 2017). Amidst persistent hot and dry conditions, the wildfire season saw 65,000 people displaced (BC Wildfire Service, 2017) and widespread impacts on air quality and human health. New records were set for area burned and the length of a provincial state of emergency (BC Wildfire Service, 2017). Projections of increased fire activity (Boulanger et al., 2014; Flannigan et al., 2009; Hope et al., 2016; Wotton et al., 2010), accompanied by increased suppression costs (Hope et al., 2016), make climate change a key consideration for fire management plans (Wildland Fire Management Working Group, 2016) and wildfire management an important component of climate change adaptation plans.

The area that was burned by wildfires in BC in 2017 was 40% greater (Figure 1) than the previous record set in 1958, based on an observational record beginning in 1950. The area burned in southern BC in 2017 was an order of magnitude (Figure 1) greater than the previous record (2009). An immediate question that was posed by forest managers, policy makers, and the public even as the events were ongoing was whether anthropogenic climate change, such as has been detected in Western Canada (Kirchmeier-Young et al., 2017; Wan et al., 2018; Figure S1 in the supporting information) played a role in intensifying this very large loss. We therefore performed event attribution analyses (National Academies of Science, Engineering, and Medicine, 2016) of both the wildfire risk factors and the area burned to assess the role of anthropogenic influence. Previous studies have identified anthropogenic influence on wildfire risk in some regions of western Canada (Gillett et al., 2004; Kirchmeier-Young et al., 2017) and the United States (Abatzoglou & Williams, 2016; Partain et al., 2016; Yoon et al., 2015), but none has previously considered a thorough evaluation of an event

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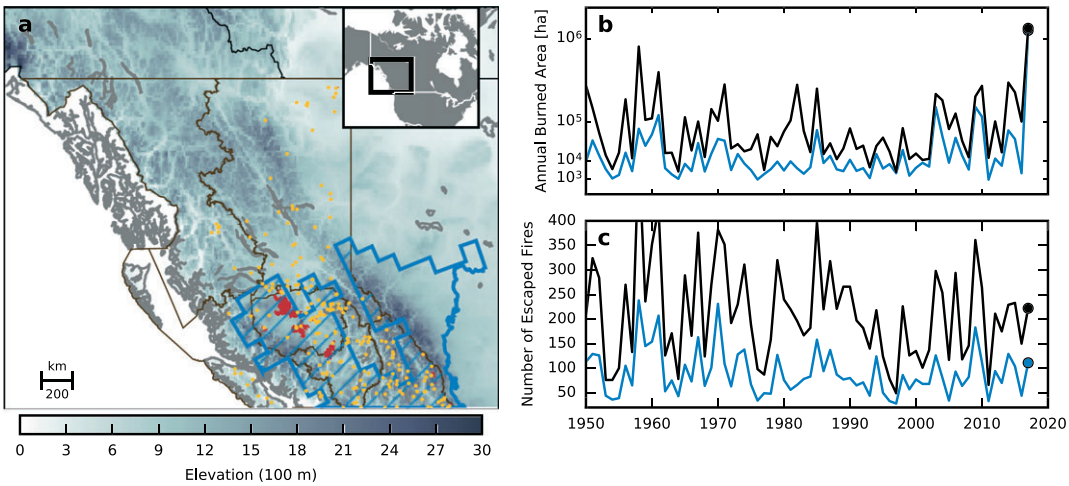

Figure 1. (a) Ignition locations of 2017 escaped fires (>4 ha in size; gold points) and perimeters of burned area (filled red). Also plotted, Southern Cordillera homogeneous fire regime zone (Boulanger et al., 2014) (blue), Southern Cordillera within British Columbia (BC; hatched), BC fire management centers (brown), and elevation (gray scale). (b) Time series of annual area burned in hectares (cube-root scale) and (c) of the number of escaped fires for all of BC (black) and the BC Southern Cordillera (blue) during 1950–2017, with a marker at 2017. The cube-root scale for the annual burned area (b) allows all years within the wide range of magnitudes to be visible.

of the scale observed in BC in 2017, nor has any previous event attribution study explicitly considered area burned.

We use a novel large ensemble (50 realizations) of regional climate model historical simulations (CanRCM4; Scinocca et al., 2016) that were bias corrected (Cannon, 2018) toward a reanalysis (MERRA2; Field et al., 2015; Gelaro et al., 2017). We focus on the Southern Cordillera homogeneous fire regime zone (Boulanger et al., 2014) found within BC, which encompasses most of the 2017 fire activity (Figure 1). The BC Southern Cordillera is generally characterized by a mixed-severity fire regime (Heyerdahl et al., 2012; Marcoux et al., 2015), historically experiencing both ground and crown (canopy) fires that influence the distribution of species and forest characteristics. Similar fire regimes are found in parts of the western United States (Odion et al., 2014).

The 2017 wildfire season began slowly, with a wet spring and lower than normal fire counts through June (BC Wildfire Service, 2017). However, hot and dry July–August conditions saw a large increase in fire activity, particularly in the south (Figure 1). A Provincial State of Emergency of record-breaking length lasted through mid-September (BC Wildfire Service, 2017). The record burned area is an order of magnitude larger than the previous record in the BC Southern Cordillera, though the full-season count of fires exceeding 4 ha in size is near average (Figure 1).

We perform an event attribution analysis to assess the role of anthropogenic climate change in the extreme wildfire season in BC during 2017. The results can be used to understand the implications of increased greenhouse gasses on a relevant and high-impact event and to help identify considerations for adaptation strategies. To assess the extreme fire season, we consider temperature and precipitation anomalies; indices describing wildfire risk; and, finally, annual burned areas.

2. Data and Methods

2.1. Data

We use a large ensemble of CanRCM4 (Scinocca et al., 2016) consisting of 50 realizations on a 50-km grid. Each realization is driven by a member of the CanESM2 (Arora et al., 2011) large ensemble (Kirchmeier-Young et al., 2017) with historical ALL (anthropogenic and natural) forcings through 2005 and extended with RCP8.5. We utilize data from 1961 to 2020.

The model realizations were bias corrected using the multivariate method of Cannon (2018), which preserves the relationship between variables. As in Kirchmeier-Young et al. (2017), the model ensemble was bias corrected toward the MERRA2 reanalysis (Gelaro et al., 2017). Local noon values required for the calculation of the fire weather indices were acquired for the MERRA2 reanalysis from the Global Fire Weather Database (Field et

al., 2015) and precipitation was taken from the Multi-Source Weighted-Ensemble Precipitation (MSWEP) data set (Beck et al., 2017).

A data set of gridded maximum (and minimum) temperature and precipitation anomalies was created by interpolating monthly values calculated from surface station observations relative to a 30-year climatology. Observational data was acquired from numerous sources and interpolated using a thin plate spline methodology.

Additional details describing the data sets (e.g., Harris et al., 2014) and processing (e.g., Amiro et al., 2004; Forestry Canada Fire Danger Group, 1992; Perrakis & Eade, 2016; Ribes et al., 2013; Van Wagner, 1987) can be found in the supporting information.

2.2. Event Attribution

Event attribution compares the probability of occurrence of an event between a scenario including anthropogenic factors and a scenario without the anthropogenic influence. As the CanRCM4 ensemble includes natural and anthropogenic forcings, we use the decade 2011–2020 to represent the current climate and an earlier decade and 1961–1970 to represent an alternative climate with reduced influence of human emissions. Much of the warming globally has occurred since the 1970s (Hartmann et al., 2013), and the difference between temperatures in these two decades is similar to the difference between all-forcing and natural-only simulations using the driving global climate model (CanESM2) in 2011–2020 (Figure S2). Additionally, though only for a single model, the use of a 50-member ensemble provides a robust sampling of internal climate variability.

For a given metric, values for each year and large ensemble realization were pooled together for two time periods: 1961–1970 and 2011-2020, resulting in 500 values for each decade (10 years × 50 realizations). A distribution was fit using a Gaussian kernel density estimator, enforcing a bound at 0 when necessary. Thresholds for the events were defined based on 2017 values from the observations (anomalies and burned area) or reanalysis (fire indices).

The probability of occurrence for the event was calculated for the current decade, p_1, based on the frequency of occurrence in the bias-corrected large ensemble simulations, and compared with the probability for the reference decade (1961–1970), p_0. The change between p_0 and p_1 can be attributed to primarily anthropogenic forcing since other external influences have only made a small contribution to temperature trends observed over this period (Bindoff et al., 2013). The fraction of attributable risk,

$$FAR = \frac{(p_1 - p_0)}{p_1}, \tag{1}$$

therefore indicates how much of the probability of the event may be attributable to anthropogenic forcing. Additionally, the probability ratio (also known as the risk ratio),

$$PR = \frac{p_1}{p_0}, \tag{2}$$

describes how many times as likely the event is due to the effects of anthropogenic forcing. Confidence intervals for the distributions (and subsequently the fraction of attributable risk and probability ratio) were determined by resampling from the pool (of 500 years) with replacement and applying the kernel density estimation and probability calculation 1,000 times.

3. Results

3.1. Temperature and Precipitation Anomalies

July–August 2017 was anomalously hot and dry in the BC Southern Cordillera, ranking first in both characteristics in a time series beginning in 1961 based on gridded station observations. Time series of simulated mean anomalies for precipitation and maximum temperature (Tmax) agree well with observations for this region (Figure 2).

Tmax shows a strong warming trend for July–August monthly mean anomalies, with distinct separation between the temperature distributions of the first and last decades (Figure 2). The fraction of attributable risk indicates that anthropogenic influences contributed approximately 96% of the probability of the observed 2017 anomaly. The probability ratio indicates that anthropogenic factors increased the likelihood of the extreme warm value observed in 2017 by over 20 times.

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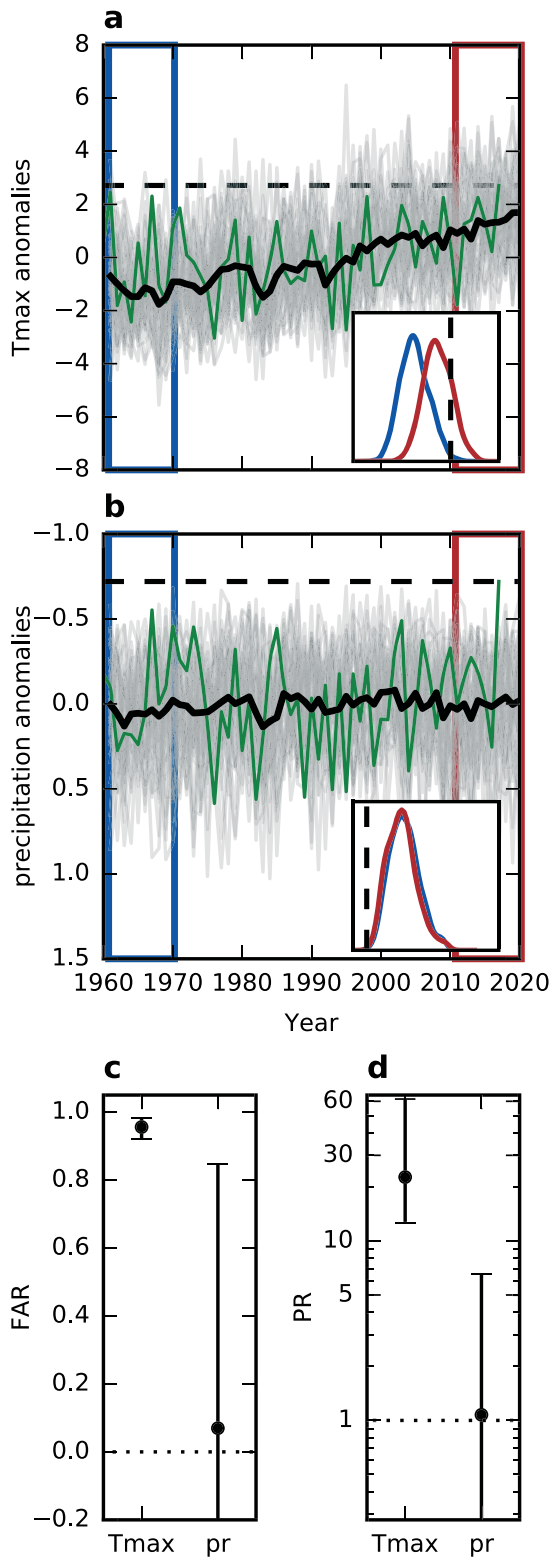

Figure 2. Time series of July–August (a) mean daily maximum temperature (Tmax, °C) and (b) mean daily precipitation (pr) anomalies. Precipitation is plotted as relative anomalies on an inverse scale. Observations are shown in green, and bias-corrected CanRCM4 realizations are in gray with the ensemble mean in bold black. Dashed lines (in a and b) mark the observed 2017 values. Anomalies (relative to 1981–2010) are expressed as differences for Tmax and ratios for precipitation, centered on 0. Probability density curves (insets) are from the CanRCM4 ensemble from decades outlined in corresponding colors. The fraction of attributable risk (FAR; c) and probability ratio (PR; d, log scale) for observed 2017 anomalies are plotted with 90% confidence intervals.

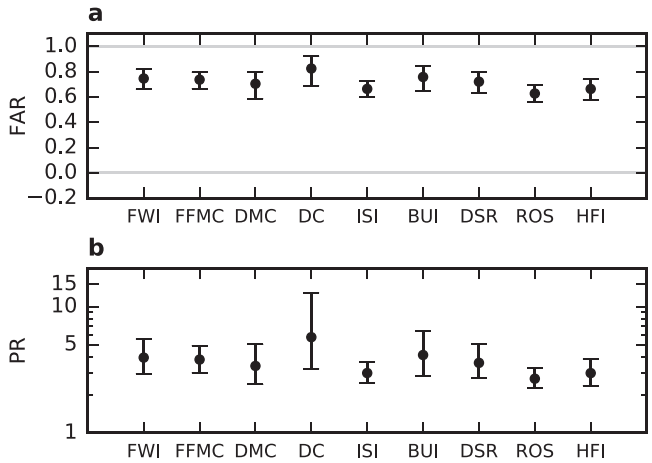

Figure 3. (a) The fraction of attributable risk (FAR) and (b) the probability ratio (PR) of exceeding the 2017 values of the fire weather and behavior indices. The metric used for each index is a regional mean 95th percentile value calculated from July–August daily values. The 2017 value is determined from the MERRA2 reanalysis. Error bars represent the 90% confidence interval. Table S1 lists the index definitions. Time series of each index and FAR and PR values for additional thresholds are shown in Figures S3–S5.

In contrast, there is no discernible trend in observed or simulated mean July–August precipitation anomalies during 1961–2020 (Figure 2b). We therefore do not identify an anthropogenic contribution to the observed 2017 precipitation anomaly, though it was a key factor in the extremity of the fire season.

3.2. Fire Weather and Behavior Indices

Warm and dry conditions through July–August led to elevated wildfire risk. Indices from the Canadian Forest Fire Danger Rating System (Wotton, 2009), which is used internationally, serve as predictors of a range of fire weather and behavior characteristics based on weather/climate variables. The CFFDRS indices, listed in Table S1, describe characteristics of fuel moisture and the spread and intensity of a potential fire. Here we will focus on the indices as a set indicative of general wildfire risk.

To describe the extremeness of the wildfire season during July–August, the 95th percentile of each index (determined from daily values) was calculated for each season and each grid box and then averaged across the region. Thresholds were determined based on values calculated similarly from the MERRA2 reanalysis product for 2017. We consider events more extreme than the designated thresholds from a fire risk perspective, which is larger values of all indices. For all of the fire indices, 60–90% of the risk (Figure 3a) and a factor of 2–4 increase in the likelihood (Figure 3b) of the extreme values from 2017 can be attributed to anthropogenic influences.

Furthermore, a few consecutive days of extreme fire risk can also have a large impact on the severity of a season's fire activity. To represent this for each index, the length of the maximum run of consecutive days exceeding an extreme threshold was calculated for each year. The thresholds were defined by the climatological 90th percentile value for July–August from the MERRA2/MSWEP data set. Anthropogenic influence has increased the likelihood of long high fire risk periods (Figure 4), contributing 55–95% of the risk.

3.3. Area Burned

Elevated fire risk can lead to large burned areas (Williams & Abatzoglou, 2016). As fire is not simulated directly in CanRCM4, we fit a regression model to predict area burned using climate variables and fire weather indices. The approach is discussed in more detail in Appendix A. Temperature (July mean) is found to be the best predictor of area burned, consistent with previous studies (Abatzoglou & Kolden, 2013; Balshi et al., 2009; Gillett et al., 2004). The regression model, with cross-validation, explains about 55% of the variance of the natural logarithm of annual area burned (Figure S9), which is consistent with other analyses in North America (Abatzoglou & Kolden, 2013; Balshi et al., 2009; Littell et al., 2009; Parisien et al., 2011; Urbieta et al., 2015). We use annual burned area, although over 85% of the area burned in the BC Southern Cordillera occurs during the summer months (June–August) and over 75% during July and August.

The regression model predictions of burned area generally capture the increasing trend and interannual variability of the observations (Figure 5a). A comparison of probability distributions shows that extreme area

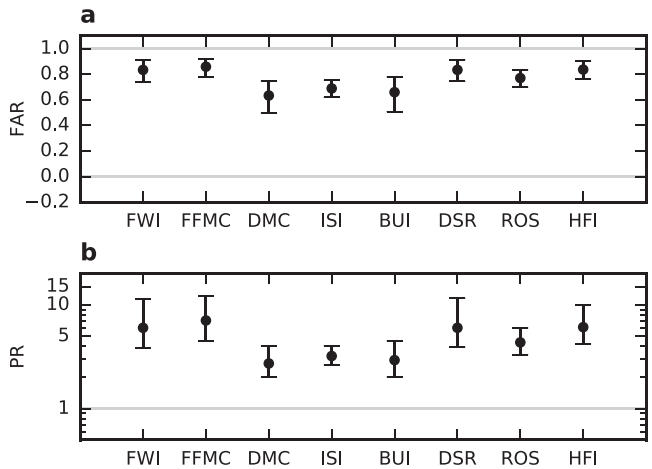

Figure 4. (a) The fraction of attributable risk (FAR) and (b) the probability ratio (PR) of exceeding the 2017 values of the length of the annual maximum run of consecutive high fire risk days. Error bars represent the 90% confidence interval. Table S1 lists the index definitions. Time series of each index and FAR and PR values for additional thresholds are shown in Figures S6–S8.

burned amounts are more likely with the inclusion of anthropogenic climate change. The 2017 amount is approximately the 99th percentile in the current decade, and annual burned areas of this same percentile are smaller by a factor of 7.1–11.0 (Figure 5b) in the decade with reduced human influence. An alternate interpretation is that 86–91% of the area burned in 2017 can be attributed to anthropogenic climate change. Additionally, anthropogenic climate change has greatly increased the frequency with which such an event can be expected to occur (Figure 5c).

The result is dependent on the regression model being realistic. Our regression model assumes that nonclimatic variability in the natural log of area burned is stationary in time and does not account for the possible influence of human factors such as changes in forest management or human ignition sources. Humans have long had a direct influence on fire activity (Bowman et al., 2011), and trends in some regions have been strongly impacted by human intervention (Fréjaville & Curt, 2017; Parisien et al., 2016; Turco et al., 2014). Syphard et al. (2017) demonstrated that climate influence on fire activity becomes less important with a strong human presence. We also do not consider directly the impacts of repeated suppression over time, which could result in larger fires, nor do we consider the pine beetle infestation that has affected BC (Kurz et al.,

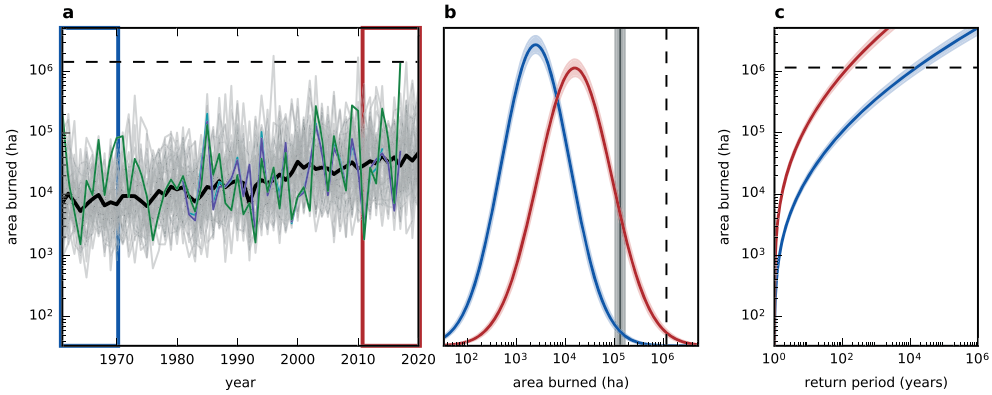

Figure 5. Time series (a, log scale) of regression-predicted annual burned area in the BC Southern Cordillera for bias-corrected CanRCM4 realizations (gray) and ensemble mean (bold), reanalysis (turquoise/purple), and observations (green). The dashed line marks the observed 2017 value. Probability distributions (b) for area burned amounts (log scale) from decades outlined in corresponding colors in (a). The gray bar indicates the area burned amount in the distribution with reduced anthropogenic influence (blue) of a corresponding percentile to the 2017 amount (dashed line) in the distribution of the current decade, which includes anthropogenic influence (red). The distributions in (b) are used to derive return periods in years for area burned amounts (c). The best-fit regression model is used (see Appendix A and Figure S9), with shading in (b) and (c) demonstrating the 90% confidence interval.

2008), although such a disturbance did not impact large-scale area burned in the United States (Hart et al., 2015). Nonetheless, consistency of our finding with attribution of an increase in fire risk and previous studies demonstrating that climate change is an important driver of changes in fire behavior in many regions of North America (Gillett et al., 2004; Littell et al., 2009; Morton et al., 2013) supports the finding of a substantial contribution of anthropogenic climate change to the risk of a burned area as large as that in 2017.

As a result of increasing temperatures and increasing wildfire risk, extreme area burned amounts like 2017 in BC are expected to become more likely in the future. In fact, the 2018 wildfire season in BC burned more area than the record-shattering season of 2017, with over 1.35 million ha (BC Wildfire Service, 2018). Since most of the area burned in 2018 occurred in the northern part of the province (compared to the southern region in 2017), the event attributions discussed above do not apply directly. However, it can be inferred that extreme warm conditions that, along with extreme dryness, contribute to high wildfire potential were made more likely by anthropogenic influence on the climate. Furthermore, the regression analysis was repeated with province-wide values, and, with less confidence than at the regional level, 84-87% of the area burned can be attributed to anthropogenic climate change (Figure S10).

4. Conclusions

The summer of 2017 saw extremely warm and dry conditions in the Southern Cordillera region of BC (Canada), and a burned area far exceeding the previous maximum. While we find no evidence that anthropogenic influence contributed to the risk of extremely dry conditions, we find that it has substantially increased the risk of warm conditions, elevated wildfire risk, and large area burned comparable to those observed.

While significant uncertainties remain in the attribution of area burned relating to the influence of nonclimatic factors, as discussed above, our finding of a significant anthropogenic contribution to the risk of extreme fire weather, based on multiple metrics and event definitions, increases the robustness of our overall result. As the climate continues to warm, we can expect that extreme wildfire seasons like 2017 in BC will become more likely in the future. Noting that changes in fire activity as a result of climate drivers can vary spatially (Kitzberger et al., 2017), other regions of the globe experience strong relationships between climate and wildfires and with strong warming trends will likely also see increases in the likelihood of extreme wildfire seasons in the future (Bedia et al., 2015; Turco et al., 2018).

The profound influence of climate change on wildfire extremes in BC demonstrated in this analysis is likely reflected in other regions and is expected to intensify in the future. As such, this relationship will require increasing attention in many sectors (Wildland Fire Management Working Group, 2016), including forest management, public health, and infrastructure.

Appendix A: Area Burned Regression

We fit a simple multiple linear regression model to describe area burned as a function of climate and fire-index predictors. The model was trained using data from MERRA2 (Gelaro et al., 2017), with precipitation from MSWEP (Beck et al., 2017) and the natural log of the annual area burned in the Southern Cordillera of BC (in 10^5 ha). Transforming the area burned using the natural log allows the assumption of a normally distributed predictand and is a common practice for regression analyses with area burned (Abatzoglou & Kolden, 2013; Littell et al., 2009; Parisien et al., 2011). Most of the predictors considered are the 95th percentile July–August values used in the event attribution analysis of the indices, though mean temperatures were also considered. The regression analysis considered one- and two-predictor models; over 20 models were tested (Figure S9; Table S2).

A leave-one-out cross-validation procedure was used to determine the best predictor sets based on an R^2 metric. Using Akaike information criterion (AIC) or root mean square error instead resulted in the same top five models, though the individual ranks differed among metrics. Including July mean temperature as a predictor greatly improved the variance explained, and thus, all of the top models use this predictor. Wan et al. (2018) have detected an anthropogenic influence in summer (June–August) temperature over BC and the neighboring Yukon. The variance explained was very similar if the predictors and log of area burned were first detrended (Table S2).

For the calculation of the event attribution metrics, following the procedure for the other variables would underestimate the variance of the distributions if a kernel density estimator was applied to the regression

predictions (conditional means). Alternatively, a normal distribution was estimated for each year and each realization with a mean equal to the regression prediction and a standard deviation equal to the regression's standard error of prediction. For each decade, a normally distributed mixture distribution was determined with each year/realization carrying equal weight. This mixture distribution was then used to calculate the event attribution metrics.

For the 2018 analysis, the regression model was trained on the same data province wide, using only July mean air temperature as a predictor. This regression model explains about 32% of the variance. Due to data availability restrictions, the model was then applied to CanRCM4 realizations before bias correction.

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