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Drought effects on large fire activity in Canadian and Alaskan forests

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Abstract
Fire is the dominant disturbance in forest ecosystems across Canada and Alaska, and has important implications for forest ecosystems, terrestrial carbon dioxide emissions and the forestry industry. Large fire activity had increased in Canadian and Alaskan forests during the last four decades of the 20th century. Here we combined the Palmer Drought Severity Index and historical large fire databases to demonstrate that Canada and Alaska forest regions experienced summer drying over this time period, and drought during the fire season significantly affected forest fire activity in these regions. Climatic warming, positive geopotential height anomalies and ocean circulation patterns were spatially and temporally convolved in causing drought conditions, which in turn enhanced fuel flammability and thereby indirectly affected fire activity. Future fire regimes will likely depend on drought patterns under global climate change scenarios.

Keywords: fire, drought, boreal forest

1. Introduction

Fire is the dominant disturbance in forest ecosystems across Canada and Alaska (McGuire *et al* 2002). Fire alters forest structure, composition and succession (Levine 1996), and has important implications for terrestrial carbon dioxide (CO_2) emissions (Kurz and Apps 1999, Amiro *et al* 2001, Zhuang *et al* 2002, 2006) and the forestry industry (Weber and Flannigan 1997). Forest fire activity in Canada and Alaska including fire occurrence and area burned increased during the last four decades of the 20th century (Podur *et al* 2002, Stocks *et al* 2002, Kasischke and Turetsky 2006). Understanding the factors that contribute to fire activity in these regions is essential for projecting future trends in fire activity under global climate change scenarios and their ecological and biogeochemical consequences (Fauria and Johnson 2006) as well as for developing and implementing effective forest management (Trouet *et al* 2006).

Analyses of the forest fire activity in Canada and Alaska during the last four decades of the past century have established that the area burned by forest fires is linked to regional warming trends (Gillett *et al* 2004), positive midtroposphere (500 hPa) anomalies (upper air blocking highs) that block zonal atmospheric circulation (Skinner *et al* 2002), teleconnection patterns (Skinner *et al* 1999, Duffy *et al* 2005, Fauria and Johnson 2006), and a combination of multiple factors that include climate, lightning strike frequency, topography and forest cover (Kasischke *et al* 2002). Here we used the Palmer Drought Severity Index (PDSI) and historical large fire databases from 1959 to 1999 to examine the relationship between moisture conditions and fire activity, and demonstrated that drought significantly affected forest fire activity in forested regions across Canada and Alaska.

2. Methods

We obtained the Canadian Large Fire Database (LFDB) from the Canadian Forest Service (Stocks *et al* 2002). The LFDB was constructed from provincial and territorial fire reports and includes digitized and georeferenced maps of final fire perimeters. This database represents a compilation of all fires greater than 200 ha that have occurred in Canada during the period between 1959 and 1999, and contains information on start location, area burned, fire start date, ignition source (human, lightning, unknown) and ecozone of fire origination.

The LFDB represents only 3.1% of the total number of Canadian fires during this period, but these fires account for 97% of the total area burned (Stocks *et al* 2002). Podur *et al* (2002) suggested that this dataset has possible biases due to forest management practices, and forest fires in low-priority areas may not have been as well documented as high-priority areas where fire might have substantial impacts on public safety, property and forest resources. We obtained the historical large fire database for Alaska from the Bureau of Land Management, Alaska Forest Service (http://agdc.usgs.gov/data/blm/fire/). This database represents a compilation of fires in Alaska between 1950 and 2005, and contains point and boundary location information for fires. It contains fires greater than 1000 acres between 1950 and 1987, and fires greater than 100 acres between 1988 and 2005. We analyzed data for the period 1959–1999 for which we had access to fire data for both Canada and Alaska.

Surface moisture conditions were characterized using the Palmer Drought Severity Index (PDSI) (Palmer 1965). The PDSI is a moisture index commonly used in fire-climate studies (Swetnam and Betancourt 1990, Hessl *et al* 2004, Trouet *et al* 2006). The PDSI incorporates the antecedent precipitation, moisture supply and moisture demand, and captures dry and wet spells (Palmer 1965). The PDSI varies roughly between −6.0 and +6.0, with negative values denoting dry spells and positive values for wet spells. Values between −0.5 and 0.5 are considered near normal. Values of −1.0 to −1.9 are interpreted as mild drought, −2.0 to −2.9 as moderate drought and −3.0 to −3.9 as severe drought. We used the global PDSI data at 2.5° × 2.5° spatial resolution from the National Center for Atmospheric Research (Dai *et al* 2004). The percentage area experiencing drought over Canada and Alaska was calculated by summing the drought-affected area (PDSI <−1.0) and then dividing by the total land area of these regions.

Using the two historical large fire databases and PDSI, we investigated the spatiotemporal relationships between fire regimes (area burned and number of fire events) and drought during the fire season (May–August; (Stocks *et al* 2002)) over Canada and Alaska for the period 1959–1999. First, we examined the trends of annual area burned, number of fire events and drought-affected area over the study period. Second, we examined the statistical relationship between fire activity and drought-affected area using standard regression diagnostics, including residuals, outliers, constant/non-constant variance and normality. Finally, we looked at the spatial patterns of fire regimes, drought, temperature and precipitation over Canada and Alaska using the fire databases and PDSI as well as the monthly temperature and precipitation dataset at 0.5° × 0.5° resolution (CRU TS 2.1) (Mitchell and Jones 2005). We used the relative risk of fire occurrence to determine whether fire is more likely to occur in dry years than non-dry (normal or wet) years. Relative risk is the ratio of the probabilities of cases having a positive outcome in the experimental and control groups (Agresti 2002). The estimate of the relative risk of fire occurrence is the ratio of the proportions of fire occurrence in dry and non-dry years. A relative risk of 1.0 corresponds to independence; a relative risk greater than 1 indicates that fire is more likely to occur in dry years than in non-dry years; a relative risk less than 1 indicates that fire is less likely to occur in dry years than in non-dry years. We produced gridded fire occurrence with 150 km × 150 km spatial resolution for each year over the period 1959–1999 from the two large fire databases, and then calculated the relative risk of fire occurrence for each grid cell.

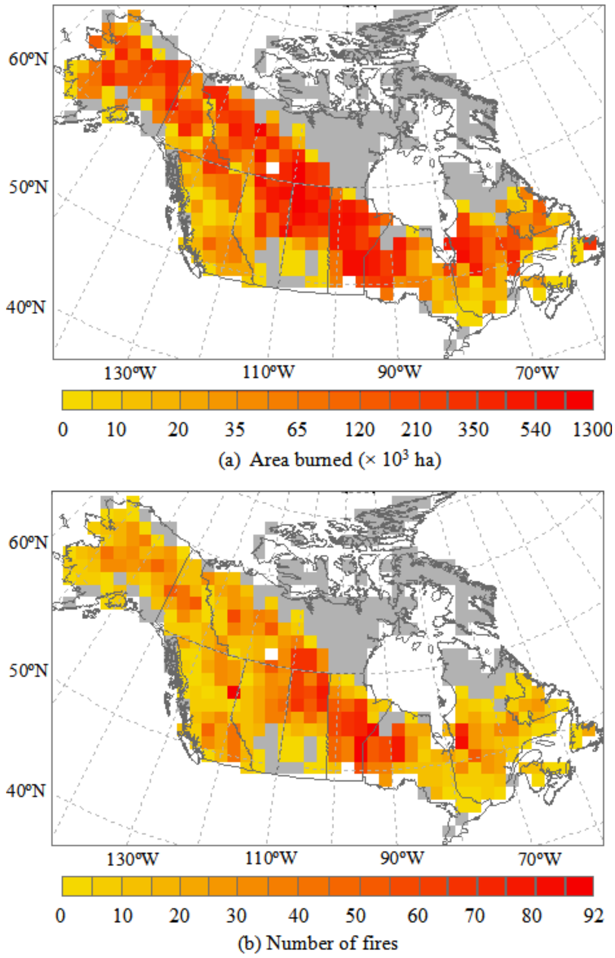

Figure 1. Total area burned over Canada and Alaska and the total number of fires during the fire season in each 150 km × 150 km grid cell from 1959 to 1999. (a) Total area burned in 10^3 ha. (b) Total number of fire events.

3. Results and discussion

The geographical distribution of forest fires over Canada and Alaska was evaluated by summing the annual area burned and the total number of fires in these regions, respectively, on a 150 km × 150 km grid for the period 1959–1999 (figure 1). Between 1959 and 1999, fires affected 8.4 × 10^5 km^2 of land in Canada and Alaska, accounting for 13.1% of the forests in these regions (figure 1(a)). Cumulatively, Manitoba, western Ontario and northern Saskatchewan suffered from more fires than other Canadian provinces and Alaska over this time period (figure 1(b)).

The annual area burned in Canada and Alaska forest regions exhibited a pronounced upward trend over the period

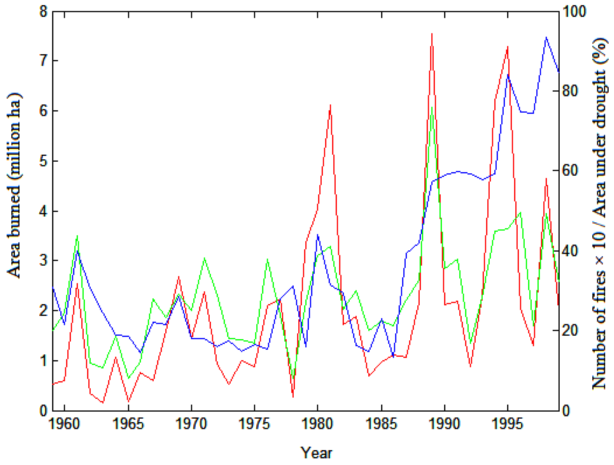

Figure 2. Annual area burned, number of fires and percentage area experiencing drought over Canada and Alaska from 1959 to 1999. The red line shows total area burned in 10^6 ha. The green line shows the total number of fire events. The blue line shows the percentage area experiencing drought over Canada and Alaska.

1959–1999 (figure 2; $r = 0.47$, $p < 0.01$), as also shown by previous studies (Podur *et al* 2002, Stocks *et al* 2002, Kasischke and Turetsky 2006). The number of fire events in these regions also significantly increased (figure 2; $r = 0.47$, $p < 0.01$). During the same period, the percentage area experiencing drought over the regions exhibited a striking upward trend (figure 2; $r = 0.74$, $p < 0.001$). The variation of annual area burned and number of fire events exhibited strong correspondence to that of the percentage area experiencing drought over time (figure 2). Large fire years were dry compared to small fire years. For example, for large fire years including 1989 and 1995, about 57% and 84% of the Canada and Alaska forest region was affected by drought, respectively. Wet years usually corresponded to small fire years.

We examined the statistical relationships between fire activity and drought-affected area across Canada and Alaska forest regions (figure 3). The residual analysis and Box–Cox transformation showed that the drought-affected area was significantly correlated with the logarithm of area burned (figure 3(a); $r = 0.49$, $p < 0.01$). With the logarithmic transformation of the response variable, the residuals exhibited constant variance (figure 3(c)), and are approximately normally distributed. This relationship between drought-affected area and area burned suggests that drought may have affected the annual area burned in Canada and Alaska, and area burned increased exponentially with drought-affected area.

We then examined the statistical relationship between number of fires and drought-affected area (figure 3). The year 1989 was characterized by 759 large fires, approximately 180% higher than the median value of the period (1959–1999), and exhibited an exceptionally large residual. This point was detected as an outlier based on the Bonferroni correction method (Faraway 2002) and thus was removed in the analysis. Residuals, Box–Cox transformation and normality analyses showed that the number of fire events was linearly correlated with drought-affected area (figure 3(b); $r = 0.56$, $p < 0.001$), demonstrating that the number of fire events was also likely affected by drought. Low moisture conditions contribute to large fire occurrence by enhancing fuel flammability, while the preceding wet years increase fuel production and thus promote

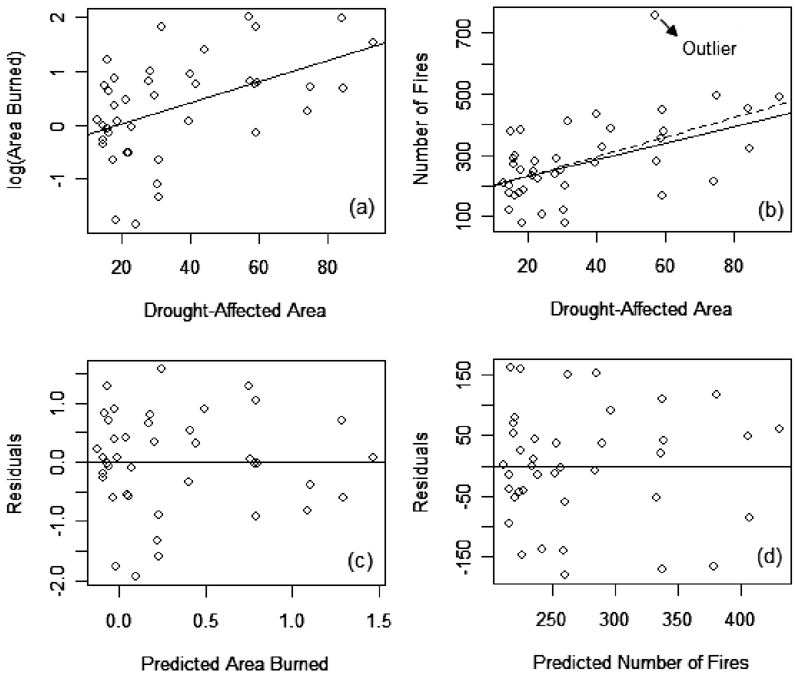

Figure 3. Scatterplots of drought-affected area versus fire activity over Canada and Alaska from 1959 to 1999: (a) drought-affected area (%) versus log (area burned in million ha); (b) drought-affected area (%) versus number of fires; (c) predicted area burned (million ha) versus residuals (observed–predicted) (million ha); (d) predicted number of fires versus residuals (observed–predicted).

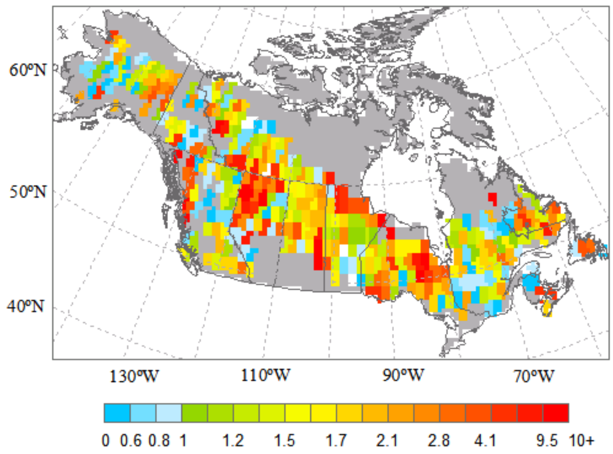

Figure 4. Relative risk of fire occurrence in forests across Canada and Alaska over the period 1959–1999.

burning in subsequent dry years (Swetnam and Betancourt 1990, Taylor and Beaty 2005).

To further demonstrate the relationship between fire activity and drought, we examined the spatial relationships between fire activity and drought in forests across Canada and Alaska. About 78% of the grid cells that had ever been burned during the period 1959–1999 exhibited relative risk values of greater than 1 (figure 4), indicating that, for the majority of the area, fire is more likely to occur in dry years than in non-dry (normal or wet) years. The Wilcoxon rank sum test of the data ($V = 68\,322.5$, $p < 0.0001$) showed that the probability of fire occurrence in dry years is significantly greater than that in normal or wet years. This demonstrates that drought significantly affected forest fire activity in Canada and Alaska over the period 1959–1999.

We also conducted spatial analyses of fires, droughts, temperature and precipitation for the two largest fire years over Canada (1989 and 1995), the largest fire year for Alaska (1969) and one small fire year for both Canada and Alaska (1963) (figure 5). In 1995, the vast majority of the forested regions over Canada and Alaska experienced drought during the fire season (figure 5(a)). Almost all fires occurred in drought-affected areas. For Alaska, Yukon Territory, Manitoba, Ontario and Quebec, temperature exhibited positive anomalies, while precipitation showed negative anomalies. The concurrence of high temperature and low precipitation during the fire season led to low moisture conditions, which enhanced fuel flammability and increased fire activity. For the Northwest Territories, Alberta and Saskatchewan, however, large precipitation deficits led to droughts in these regions despite negative temperature anomalies.

In 1989, drought affected all of Canada except the Northwest Territories, southwestern British Columbia and southeastern Ontario, and a small portion of Alaska. Similarly, most of the fires occurred in drought-affected areas (figure 5(b)). For Yukon Territory, Northwest Territories and Manitoba, both temperature and precipitation during the fire season showed positive anomalies. Although precipitation during the fire season is at or above normal, exceptionally high temperature resulted in high evapotranspiration, leading to low soil moisture conditions. For Ontario and Quebec, the concurrence of high temperature and low precipitation during the fire season resulted in low moisture conditions, which enhanced fuel flammability and increased fire activity.

In 1969, Alaska and western Canada experienced drought during the fire season (figure 5(c)). Similar to 1995 and 1989, most fires in 1969 occurred in drought-affected areas. Notably, the entire forested region over Canada and Alaska exhibited negative temperature anomalies. For Alaska, northwestern Yukon Territory, eastern British Columbia, Saskatchewan and Manitoba, large precipitation deficits caused low soil moisture conditions despite negative temperature anomalies. For southeastern Yukon Territory and western Northwest Territories, precipitation showed slightly positive anomalies while temperature showed slightly negative anomalies, which led to mild drought conditions.

In the small fire year of 1963, only southeastern Canada experienced drought during the fire season (figure 5(d)). Likewise, the majority of the fires occurred in drought-affected areas. High temperature or precipitation deficits caused low moisture conditions.

Our spatial analyses show that drought directly affected forest fire activity, while temperature or precipitation indirectly affected fire activity by influencing moisture conditions. Our results showed that the concurrence of high temperature and low precipitation, or their separate effects, could all lead to drought, which enhances fuel flammability and thereby indirectly controls fire occurrence. We also found that the effects of temperature or precipitation vary spatially and temporally.

Taken together, our spatiotemporal analyses demonstrated that drought directly affected large fire activity in the Canada and Alaska forest regions from 1959 to 1999. The correlations found by Gillett *et al* (2004) between area burned and climatic warming in Canada are likely due to the causal relationship between climatic warming and summer dryness in middle-to-high latitudes of North America (Wetherald and Manabe 1999). The established link between positive midtroposphere (500 hPa) anomalies and fire occurrence (Skinner *et al* 2002) lies in the understanding that the positive geopotential height anomalies block the movement of moist maritime air masses (Flannigan and Wotton 2001), and the subsistence of warming and drying air contributes to the development of a water deficit (Girardin *et al* 2004). Previous studies also show that large fire years in Canada and Alaska are linked to larger-scale ocean circulation patterns such as the Pacific Decadal Oscillation (PDO), El Niño Southern Oscillation (ENSO) and Arctic Oscillation (AO) (Skinner *et al* 1999, Duffy *et al* 2005, Fauria and Johnson 2006). These ocean circulation patterns likely modulate drought variability at the decadal scale (Girardin *et al* 2004). Thus, climate variability and change, positive geopotential height anomalies and ocean circulation patterns were spatially and temporally convolved in causing drought conditions and thereby indirectly affected fire activity.

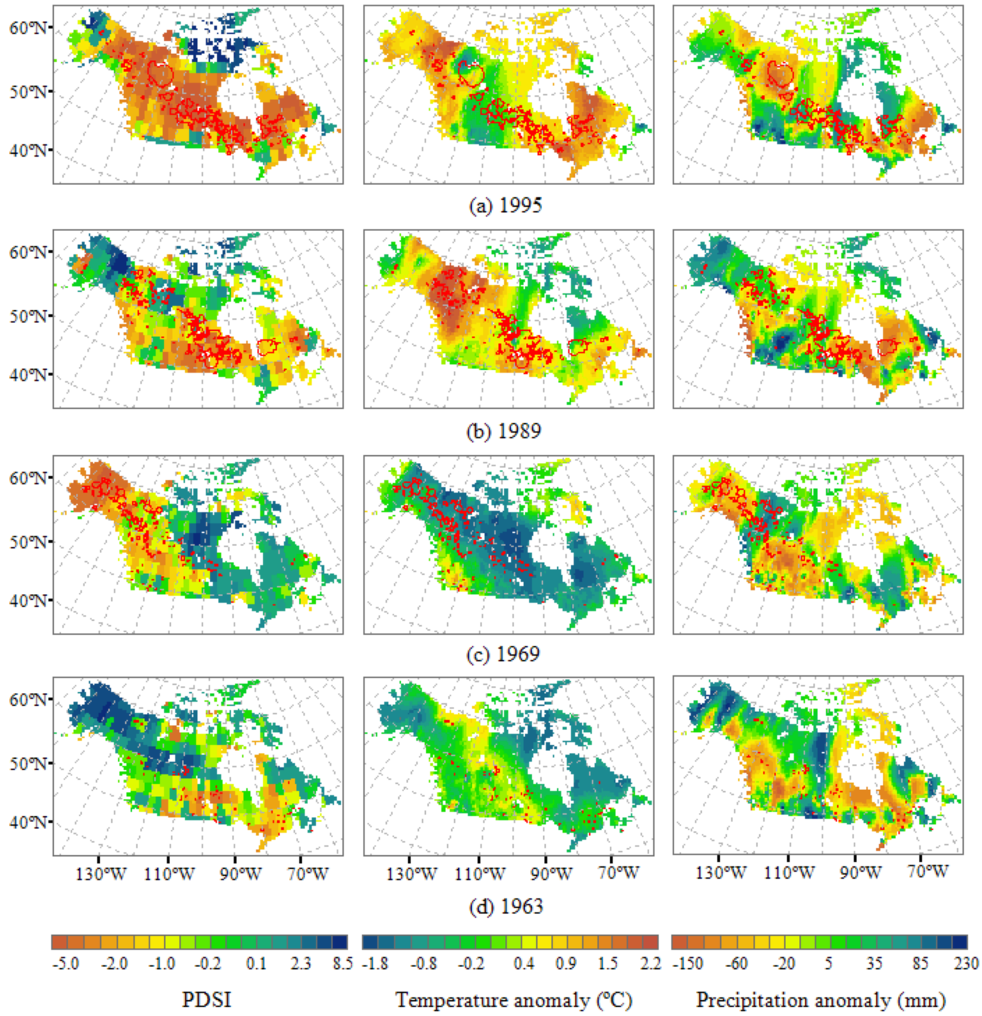

Figure 5. The spatial patterns of forest fires and droughts during the fire season over Canada and Alaska for (a) 1995, (b) 1989, (c) 1969 and (d) 1963. The red circles represent fire events. A circular buffer zone was created for each fire event surrounding its center location in the Geographical Information System (GIS), with the perimeter representing the boundary of the fire event and the radius representing four times the actual radius of the fire.

4. Conclusions

We found that forest regions in Canada and Alaska experienced summer drying during the period 1959–1999, and drought directly affected forest fire activity in these regions. Climate variability and change, positive geopotential height anomalies and ocean circulation patterns were spatially and temporally convolved in causing drought conditions, which in turn enhanced fuel flammability and led to fire activity.

Future fire regimes in forested regions over Canada and Alaska will likely depend on drought patterns under global climate change scenarios. High-frequency influences like the ENSO and PDO may result in severe extended drought events, which may in turn lead to large fire years. The increase in projected fire weather severity and fire occurrence in boreal forests in North America (Flannigan *et al* 2005) will have important implications for terrestrial CO_2 emissions, forest ecosystems and the forestry industry in these regions.

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