Wildfires in the southern Canadian Rocky Mountains and their relationship to mid-tropospheric anomalies

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In this paper we present evidence for a large-scale (synoptic-scale) meteorological mechanism controlling the fire frequency in the southern Canadian Rocky Mountains. This large-scale control may explain the similarity in average fire frequencies and timing of change in average fire frequencies for the southern Canadian Rocky Mountains. Over the last 86 years the size distribution of fires (annual area burned) in the southern Canadian Rockies was distinctly bimodal, with a separation between small- and large-fire years at approximately 10–25 ha annual area burned. During the last 35 years, large-fire years had significantly lower fuel moisture conditions and many mid-tropospheric surface-blocking events (high-pressure upper level ridges) during July and August (the period of greatest fire activity). Small-fire years in this period exhibited significantly higher fuel moisture conditions and fewer persistent mid-tropospheric surface-blocking events during July and August. Mid-tropospheric surface-blocking events during large-fire years were teleconnected (spatially and temporally correlated in 50 kPa heights) to upper level troughs in the North Pacific and eastern North America. This relationship takes the form of the positive mode of the Pacific North America pattern.


Introduction

In the past, forest ecologists have favored small-scale spatial and temporal explanations for changes in average fire frequency. Habitat types, topographic slope, aspect and elevation, forest age, and fire suppression (see Knight1987) have all been proposed as important in causing small-scale changes in fire frequencies. These explanations were often based on observation, description, or comparison frequently without satisfactory statistical designs (Johnson and Gutsell 1994) and rarely with precise causal mechanisms. Here we propose a large-scale explanation for the spatiotemporal changes in fire frequency. We examine a causal connection between synoptic-scale (large-scale) weather patterns and surface temperature, precipitation, forest fuel moisture, and the area burned by lightning-caused fires.

These larger scale mechanisms became of interest because the fire frequency in the southern Canadian Rockies could not be adequately attributed to small-scale mechanisms (Masters 1990; Johnson et al. 1990; Johnson and Larsen 1991). A larger scale mechanism seemed likely because the average fire frequency (approximately 0.01 per year, Table 1) was remarkably uniform over 20 500 km² in the southern Cana-
Table 1. Fire frequency studies in the southern Canadian Rocky Mountains and adjacent Columbia Mountains based on stand-origin (time since last fire) maps

<table>
<thead>
<tr>
<th>Study area</th>
<th>Size (km²)</th>
<th>Time period</th>
<th>Fire cycle (years)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alberta</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kananaskis Watershed</td>
<td>1300</td>
<td>1980–1730</td>
<td>90</td>
<td>Johnson and Larsen 1991</td>
</tr>
<tr>
<td>British Columbia</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kootenay National Park</td>
<td>1400</td>
<td>1928–1788</td>
<td>130</td>
<td>Masters 1990</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1760–1519</td>
<td>80</td>
<td></td>
</tr>
</tbody>
</table>

Note: The fire cycle is the time required to burn an area equal to the study area at least once and equals the inverse of the average fire frequency (Johnson and Van Wagner 1985). Note the similar timing of change in fire cycle between studies.

quasi-geostrophic model; see, e.g., Daley 1991) provided a mechanism for explaining these periods of major fire activity and the large-scale similarity of the fire frequencies.

Surface-blocking high-pressure systems are associated with persistent upper level ridges in the mid-troposphere, which cause a split in the westerly flow, diverting the eastward progression of low-pressure systems (troughs) north and south of the ridge (Lamb 1972). Because the precipitation associated with a low-pressure system is effectively "blocked" from the region of persistent high pressure, extended periods of above-normal temperature and below-normal precipitation and humidity result (Musk 1988). These dry, warm surface conditions contribute significantly to fuel drying, resulting in low fuel moisture and high fire danger (Street 1985; Turner 1972).

The temporal scale on which mid-tropospheric blocking events operate extends from days to weeks (Daley 1991), allowing for long sequences of days with extreme drying conditions. Mid-tropospheric blocking events operate on a spatial scale (Daley 1991) that is regional (100–1000 km) rather than local (1–100 km) and therefore are effective in reducing fuel moisture over relatively large areas in a given period of time. Consequently, the coupling of specific surface weather and specific circulation anomalies in the mid-troposphere provides a mechanism to compare at compatible scales how forest fuels over relatively large areas are subjected to extreme drying conditions for extended periods of time.

In this paper, we show that there is a division in annual area burned that separates large-fire years and small-fire years in the southern Canadian Rocky Mountains. In turn, this division is related to differences in fuel moisture (associated with temperature and precipitation patterns) that were caused by mid-tropospheric anomalies in the Northern Hemisphere. An important difference between our approach and traditional fire case studies (Street and Stocks 1983; Stocks and Flannigan 1987) is that we do not emphasize individual fires but the total annual area burned.

Study Site

The study area is located within the southern Canadian Rocky Mountains extending southeasternly between approximately 115°W and 120°W and 50°N and 54°N (Fig. 1). The study area includes Banff National Park and the Bow-Crow Forest Reserve in Alberta and Kootenay and Yoho national parks in British Columbia. Banff National Park occupies both the Main Ranges and Front Range, the

![Fig. 1. Location of the study area in the southern Canadian Rocky Mountains.](image-url)
Engelmann spruce and lodgepole pine are given by Johnson and Fryer (1989). The fuel types (cf. Forestry Canada Fire Danger Group 1992) of the study area are classified into Immature Lodgepole Pine (C4), Mature Lodgepole Pine (C3), Boreal Spruce (C2), and Leafless Aspen (D1).

The climate in the Main Ranges of the southern Canadian Rocky Mountains is characterized by high winter precipitation and low summer precipitation. Minor peaks in summer precipitation in the Main Ranges occur in June and August and are due to local convective activity associated with the incursion of warm continental air masses from the eastern Plains (Nkemdirim and Weber 1976; Janz and Storr 1977). The climate of the Front Range is characterized by low winter precipitation and high summer precipitation. The major precipitation peak in the Front Range occurs in June and is the result of the Alberta Low, which develops on the east side of the Front Range (Hare and Hay 1974). A secondary peak in precipitation that occurs in August is largely due to local convective activity caused by surface heating (Nkemdirim and Weber 1976; Janz and Storr 1977). The June peak in precipitation is evident throughout the southern Canadian Rocky Mountains and is amplified eastward from the Main Ranges to the Plains, where it becomes the only summer precipitation peak.

Both lightning-caused and anthropogenic fires occur from April to October. But the greatest areas are burned by natural fires in July and August, whereas the largest anthropogenic fires occur during April and May (Alberta Forest Service and National Parks, Fire Records). Over the last 100 years, fires greater than 400 ha have almost always been caused by lightning (E.A. Johnson and D.R. Wowchuk, unpublished data).

Methods

Sources of data


Thirty-five years (1954–1988) of daily (00:00 universal time code) 50 kPa geopotential height data (April 1 – October 31) were obtained from the Canadian Climate Centre, Atmospheric Environment Service, Toronto, Ontario, for 455 points in the Northern Hemisphere grid of 5° latitude by 10° longitude. A 50 kPa anomaly is calculated by subtracting the normal (1954–1988) 50 kPa height from the observed 50 kPa height at any particular place and time.


There were significant ($p < 0.05$) positive correlations in Drought Code values at climatological stations within and between Banff, Yoho, and Kootenay national parks and the Bow-Crow Forest Reserve, allowing one station (Banff) to adequately characterize the regional fire weather.

Annual area burned

Annual area burned is defined as the total area burned by lightning-caused fires in a region during a single fire season (April 1 – October 31). The regions are defined in order of decreasing size and length of record: 1961–1988 (28 years), which represents 20 500 km$^2$, the complete overlap of all data sets (BNP, KNP, YNP, BC); 1951–1988 (38 years), which represents 9360 km$^2$ (BNP, KNP, YNP); 1921–1988 (68 years), which represents 8047 km$^2$ (BNP and KNP); and 1902–1988 (87 years), which represents 6641 km$^2$ (BNP). The annual areas burned for each period were ranked from largest to smallest (annual area burned) and plotted in descending order on a logarithmic scale against rank on a linear scale to distinguish between large-year fires and small-fire years. The percent area burned by large fires was also determined from data for the period 1961–1988.

Fuel moisture

The Drought Code of the Canadian Fire Forest Weather Index System (Van Wagner 1987) is a drying rate model that relates the daily atmospheric temperature, humidity, and precipitation to the process of large fuel drying. The Drought Code models the daily moisture content of the deep compact layer of organic matter (approximately 25 kg dry weight per square metre) in a standard fuel type (Mature Lodgepole Pine, C3), which has an equilibrium drying time of 52 days (Van Wagner 1985). The Drought Code of the Canadian Fire Forest Weather Index has been extensively used and validated in forested regions of Canada (Van Wagner 1985, 1987).

We used moisture content of this slow-drying fuel because its equilibrium drying time matched the synoptic weather time scale (upper level ridge) of 30 to 50 days. The calculation of the daily Drought Code requires daily mean temperature, daily precipitation, daily length correction, and the previous day’s Drought Code value. The day-length correction accounts for the changing amount of time (day length) available for fuels to dry over the duration of the fire season (Van Wagner 1987 for equations).

The daily Drought Code pattern over the fire season was characterized by the third-order polynomial function: $y = a + bx + cx^2 + dx^3$, where $y$ is daily Drought Code value and $x$ is day of the fire season (April 1 – October 31 equals 1 to 214). Estimates of $a$, $b$, $c$, and $d$ were estimated for the daily Drought Code of each year from 1954 to 1988 using a general linear model (SAS Institute Inc. 1985) that included Julian date, date$^2$, and date$^3$ as covariates, fire group (large- or small-fire years) and years within fire group (year) as main effects, and interactions between the covariates and main effects. The period 1954–1988 represents the longest period for which area-burned data, fire-weather data, and synoptic-weather data were simultaneously available and therefore was the period used in the analysis.

Blocking high-pressure systems

 Blocking high-pressure systems were defined as ≥10 consecutive days with an above-normal 50 kPa height and ≤1.5 mm precipitation at the Banff townsite (51°11'N, 115°36'W). The criterion of ≥10 days was chosen, as it is an average duration of blocking high-pressure systems (Knox and Hay 1985; Shukula and Mo 1983; Rex 1950). Blocking durations of less than 10 days have been found to have little influence on area burned (Flannigan and Harrington 1988). The 1.5-mm precipitation threshold was used because it is known to be highly correlated with area burned (Flannigan and Harrington 1988).

For the fire seasons 1954–1988 the daily 50 kPa height anomaly was matched to the daily precipitation. Sequences of ≥10 days meeting the 50 kPa height anomaly and precipitation criteria were chronologically plotted to compare the temporal distribution of blocking high-pressure systems between years.

Circulation anomalies in the mid-troposphere

Composite mean 50 kPa height fields were constructed for large-fire years (as defined by the annual area burned) for different time periods in the fire season. The strategy for defining seasonal divisions follows Knox and Lawford (1990), with the difference that they divide the growing season and here we divide the fire season. The fire season was divided as follows:

<table>
<thead>
<tr>
<th>Circulation anomalies in the mid-troposphere</th>
<th>Spring to early summer</th>
<th>Mid to late summer</th>
<th>Fall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>April, May, June</td>
<td>July, August</td>
<td>September, October</td>
</tr>
</tbody>
</table>

The composite mean 50 kPa height fields were constructed for large-fire years by plotting the respective mean seasonal 50 kPa height values for large-fire years on a 455-point, 5° latitude by 10° longitude grid of the Northern Hemisphere for the period 1954–1988.
Fig. 2. Rank-order distributions of annual area burned in the southern Canadian Rocky Mountain study area (see text for explanation of data sets). Individual graphs have been shifted to make them legible.

**Results**

*Annual area burned*

Figure 2 shows the annual area burned ranked in descending order for 1961–1988, 1951–1988, 1921–1988, and 1902–1988. These distributions represent different record lengths for different sizes of area. All four distributions showed a similar break in their distributions at approximately 10–25 ha despite the different periods and areas they represent. Consequently, large-fire years were defined as those years with ≥10–25 ha of annual area burned and small-fire years were defined as years with <10–25 ha of annual area burned (Fig. 2). Regression lines are drawn using the median regression technique of Ferrell (1958). The 10–25 ha division between large- and small-fire years seems particularly small and could easily have been burned in one afternoon. However, the division does appear to be consistent with the data available. We do not believe that this boundary is applicable to other areas. The question is whether the small value of the division is the result of the limitation of the data or whether it reflects some fire-weather threshold in the southern Canadian Rockies.

*Fuel moisture*

The polynomial function used to estimate the daily Drought Code pattern (Fig. 3) revealed a significant difference between large- and small-fire years (day × group, day² × group, day³ × group) as well as a significant difference between years within a fire class (day × year(group)) Table 2).

The start-up Drought Code value of the function large-fire year was significantly greater ($p < 0.05$) than the start-up Drought Code of the function small-fire year. Further, the polynomial function of the Drought Code pattern predicted significantly ($p < 0.05$) greater Drought Code values throughout the season during large-fire years ($\hat{y} = 225.07 - 2.0480x + 0.0529x^2 - 0.0007x^3$) than during small-fire years ($\hat{y} = 190.2 - 1.2060x + 0.0340x^2 - 0.0002x^3$).

*Blocking high-pressure systems*

In both the large- and small-fire years 97% of the lightning-caused fires began in July–August (Fig. 4). Blocking events of ≥10 days and ≤1.5 mm precipitation occurred more frequently during the July–August period of large-fire years than during this same period in small-fire years (Fig. 4). However, in small-fire years more blocking events occurred in spring – early summer (April–June) and fall (September–October) than in mid to late summer (July–August).
Fig. 4. Temporal distribution of (top) lightning-caused fire starts and (bottom) blocking events in the southern Canadian Rocky Mountain study area from 1954 to 1988 (see text for definition of surface-blocking high-pressure system).

**TABLE 2.** General linear model equations characterizing the daily Drought Code patterns of large-fire and small-fire years

<table>
<thead>
<tr>
<th>Coefficients estimated</th>
<th>Source</th>
<th>df</th>
<th>Mean square</th>
<th>F</th>
<th>P &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Group</td>
<td>1</td>
<td>172 548.89</td>
<td>65.99</td>
<td>0.0001</td>
</tr>
<tr>
<td></td>
<td>Year (group)</td>
<td>33</td>
<td>586 655.50</td>
<td>224.36</td>
<td>0.0</td>
</tr>
<tr>
<td>b</td>
<td>Day</td>
<td>1</td>
<td>609 070.57</td>
<td>232.93</td>
<td>0.0001</td>
</tr>
<tr>
<td></td>
<td>Day × group</td>
<td>1</td>
<td>40 463.05</td>
<td>15.47</td>
<td>0.0001</td>
</tr>
<tr>
<td></td>
<td>Day × year (group)</td>
<td>33</td>
<td>592 164.24</td>
<td>226.46</td>
<td>0.0</td>
</tr>
<tr>
<td>c</td>
<td>Day²</td>
<td>1</td>
<td>3 692 863.31</td>
<td>1412.28</td>
<td>0.0001</td>
</tr>
<tr>
<td></td>
<td>Day² × group</td>
<td>1</td>
<td>173 369.49</td>
<td>66.30</td>
<td>0.0001</td>
</tr>
<tr>
<td></td>
<td>Day³</td>
<td>1</td>
<td>4 682 837.70</td>
<td>1790.88</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>Day³ × group</td>
<td>1</td>
<td>250 173.24</td>
<td>95.67</td>
<td>0.0001</td>
</tr>
<tr>
<td>Error mean square</td>
<td>7402</td>
<td></td>
<td>2 614.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Circulation anomalies in the mid-troposphere**

Figure 5 shows the composite mean 50 kPa height field and the anomalous 50 kPa height field for large-fire years in spring. The anomalous 50 kPa height field for large-fire years in spring was characterized by a significant \( t = 1.935, 0.10 > p > 0.05, \text{df} = 29 \) positive height anomaly centered over the eastern-central Pacific Ocean (Table 3).

Figure 6 shows the composite mean 50 kPa height field and the anomalous 50 kPa height field for large-fire years in summer. The anomalous 50 kPa height field for large-fire
TABLE 3. Significance level of 50 kPa anomaly centers during large-fire years

<table>
<thead>
<tr>
<th>Lat.</th>
<th>Long.</th>
<th>Anomaly (dam)</th>
<th>Significance (P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring (N = 30)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25°N</td>
<td>130°W</td>
<td>+0.957</td>
<td>&lt;0.10</td>
</tr>
<tr>
<td>60°N</td>
<td>160°E</td>
<td>+1.510</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td>45°N</td>
<td>170°W</td>
<td>-0.847</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td>50°N</td>
<td>100°W</td>
<td>-1.554</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td>55°N</td>
<td>40°W</td>
<td>+1.330</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td>25°N</td>
<td>30°W</td>
<td>-0.393</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td>75°N</td>
<td>100°W</td>
<td>+1.569</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td>65°N</td>
<td>10°W</td>
<td>-0.636</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td>Summer (N = 20)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50°N</td>
<td>120°W</td>
<td>+1.643</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>80°N</td>
<td>100°E</td>
<td>+2.145</td>
<td>&lt;0.10</td>
</tr>
<tr>
<td>50°N</td>
<td>100°E</td>
<td>-1.072</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>45°N</td>
<td>60°W</td>
<td>+1.476</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>40°N</td>
<td>180°W</td>
<td>+1.235</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>35°N</td>
<td>90°W</td>
<td>-1.068</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>25°N</td>
<td>20°E</td>
<td>-1.102</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>20°N</td>
<td>140°W</td>
<td>+1.003</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Fall (N = 20)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>65°N</td>
<td>100°E</td>
<td>+1.112</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td>55°N</td>
<td>160°E</td>
<td>-1.696</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td>35°N</td>
<td>140°W</td>
<td>+1.188</td>
<td>&lt;0.10</td>
</tr>
<tr>
<td>55°N</td>
<td>120°W</td>
<td>-2.241</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td>65°N</td>
<td>70°W</td>
<td>+2.762</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>50°N</td>
<td>30°W</td>
<td>-2.202</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td>55°N</td>
<td>30°E</td>
<td>-1.216</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td>40°N</td>
<td>10°E</td>
<td>+0.754</td>
<td>&gt;0.05</td>
</tr>
</tbody>
</table>

Note: N, number of months.

years in summer was characterized by a significant (t = 2.373, p < 0.05, df = 19) positive height anomaly centered over Alberta and a significant (t = 3.538, p < 0.05, df = 19) negative height anomaly centered over the southeastern United States (Table 3).

The anomalous 50 kPa height field for large-fire years in fall (Fig. 7) was characterized by a significant (t = 1.800, 0.10 > p > 0.05, df = 19) positive height anomaly over the east-central Pacific Ocean and a significant (t = 2.162, p < 0.05, df = 19) positive height anomaly over Baffin Island (Table 3).

Notice the alternation of anomaly sign from east–west and north–south in Figs. 5–7. Note particularly the significant positive anomaly in summer (July–August) in western Canada for large-fire years (Fig. 6) and how it is opposed upstream and downstream by negative anomalies.

Discussion

In the coniferous ecosystems of the southern Canadian Rockies (Fig. 1), fires have burned on average every 100 years (Table 1). Fires during years with large annual area burned had high intensity (active crown fires), high rates of spread, and large duff consumption. These large fires accounted for the majority of the area burned over the 86 years of study (e.g., 2% of the total number of lightning fires accounted for 95% of the total area burned between 1961 and 1988). In other words, lightning-fire frequency was characterized by few, infrequent large fires, which in turn determined the forest age mosaic. The large fires occurred under weather conditions that caused very dry fuels (i.e., higher temperatures, lower humidity, and lower precipitation). Often high winds are associated with rapid fire spread and large areas burned (Newark 1975; Nimchuk 1983; Janz and Nimchuk 1985; Fryer and Johnson 1988). The time and space scales of this study do not allow the incorporation of particular periods of high rate of spread in individual fires (high wind) because of the averaging involved. Upper air data (50 kPa) are observed at a 2- to 3-month averaging time scale and area burned, at an annual time scale.

The key to understanding these large-fire years lies in correctly matching the temporal and spatial scales of the atmospheric mechanism to the fuel moisture conditions asso-
associated with the large areas burned. Here we have shown empirically that large-fire years have been characterized by low fuel moisture conditions that are a consequence of regional and hemispheric anomalies in the circulation of the atmosphere.

Large-fire years and small-fire years were defined according to patterns during the past 35 years in the southern Canadian Rockies (20 500 km²), during which there has been a natural partitioning into large-fire years and small-fire years based on the annual area burned (Fig. 2). Data from a longer record (87 years) but a smaller area (6641 km²) gave the same result (Fig. 2).

Fuel moisture has been shown to be closely related to area burned (Harrington et al. 1983) and to the amount of fuel available for combustion (Turner 1972). The Drought Code of the Canadian Fire Weather Index system (equilibrium drying time of 52 days) was used to characterize the fuel moisture conditions of large-fire years and small-fire years because it best matched the time-averaging interval (weeks to months) of the mid-tropospheric blocks known to be correlated with large fires (Janz and Nimchuk 1985).

Large-fire years had higher Drought Code values (lower fuel moistures) than small-fire years throughout the fire season, indicating that the weather during large-fire years was different from during small-fire years. The largest difference in fuel moisture content between large-fire years and small-fire years occurred during July and August (Fig. 3). This is the same period when more mid-tropospheric blocks occurred during large-fire years (Fig. 4) and the tendency for a positive 50 kPa height deviation occurred over western Canada during
large-fire years (Fig. 6). July–August was also the period when most of the area was burned and most of the lightning-fire starts occurred (Fig. 4).

The western Canada positive anomaly is part of an anomalous circulation pattern (teleconnection) observed in the Northern Hemisphere called the Pacific North American (PNA) pattern (Dickson and Namias 1976; Namias 1978; Wallace and Gutzler 1981; Horel and Wallace 1981; Rogers 1981; Douglas et al. 1982; Barnston and Livezey 1987; Weber 1990). This PNA pattern involves three or four "centers of action" (geographical locations that are temporarily correlated, i.e., in 50 kPa height, sea-level pressure, temperature) and two modes (Wallace and Gutzler 1981; Barnston and Livezey 1987). The positive mode of the PNA pattern involves a negative 50 kPa height deviation in the North Pacific Ocean, a positive 50 kPa height deviation over western Canada, and a negative 50 kPa height deviation over the southeastern United States. The negative mode of the PNA pattern has the opposite signs of the positive mode of the PNA pattern: positive, negative, positive, respectively. The anomalous 50 kPa height field for large-fire years in summer resembles the positive mode of the PNA pattern (Fig. 6). Recently Knox and Lawford (1990) have shown that this PNA pattern is associated with summer drought in the grassland regions of western Canada.

The dynamical mechanism that causes the PNA teleconnection pattern to establish during the summer (Knox and Lawford 1990; Weber 1990) or winter (Wallace and Gutzler 1981; Barnston and Livezey 1987) is not yet fully understood. The PNA pattern was first interpreted as a mid-latitude response to anomalous heating in the tropical Pacific associated with the Southern Oscillation (Horel and Wallace 1981). However, a study by Simmons et al. (1983) has shown that this cannot be the only explanation, since the PNA pattern still occurs when the position of the heat source in the tropics varies. The PNA pattern is most commonly associated with an unstable mode of the wintertime Northern Hemisphere circulation (Simmons et al. 1983) that can be excited or amplified by anomalous heating in the tropical Pacific (Philander 1990).

Results of Simmons et al. (1983) also indicate that the generation and maintenance of the PNA teleconnection pattern is associated with barotropic instability localized in the North Pacific Ocean. This region of barotropic instability is characterized by barotropic conversion of energy from the time-mean flow to the anomalies associated with the PNA, thereby strengthening the anomalies. The anomalies over western Canada and the southeastern United States have been interpreted as wave-like structures emanating from the anomaly in the North Pacific Ocean that result from very low frequency Rossby-wave dispersion (Nakamura and Tanaka 1987). The dynamical mechanism generating the PNA in summer may be different from that in winter, as the energetics of the anomalies differ qualitatively between the two seasons (Sheng and Derome 1991). Further, the polarity of the two different PNA modes seems to be associated with the position of the Pacific jet stream (Nakamura and Wallace 1991). The positive mode of the PNA is associated with a southward-shifted Pacific jet stream, and the negative mode is associated with a northward-shifted Pacific jet stream.

The apparent link between circulation anomalies in the mid-troposphere and large-fire years in the southern Canadian Rockies is consistent with the results of other studies that have attempted to explain drought in North America in this context (Namias 1955; Namias 1982; Trenberth et al. 1988; Knox and Lawford 1990). Also, in a recent study in the southwestern United States (Swetnam and Betancourt 1990) fire occurrence was related to circulation anomalies in the tropical Pacific associated with the Southern Oscillation. Though there appears to be a similar synoptic-scale mechanism generating the critical fuel moisture conditions associated with fire in the southern Canadian Rockies and in the southwestern United States, it is clear they are associated with separate, teleconnection patterns (Philander 1990).

Conclusion

The landscape-scale pattern of forest ages (time since last fire) in the southern Canadian Rockies indicates that all stands eventually burn (Table 1). Less than 5% of the area goes without fire for even 200 years. The forest age pattern may be the consequence of infrequent years with large lightning fires, which are related to extreme fuel drying during mid-tropospheric blocking patterns. These mid-tropospheric anomalies over the southern Canadian Rockies appear to be related to mid-tropospheric pressure anomalies in the North Pacific. Consequently, the large-scale pattern of forest times since last fire in the southern Canadian Rockies appears to be the result of an even larger scale pattern in Northern Hemisphere atmospheric circulation and possibly in Pacific Ocean water temperatures and circulation. A more complete understanding of the physical mechanisms responsible for the maintenance of anomaly patterns in the circulation of the Northern Hemisphere (specifically, the Pacific Ocean) is required to make predictions about the frequency of circulation anomalies (blocking events) and thus the occurrence of large-fire years in the southern Canadian Rockies. From the results of this study, any changes in the frequency of circulation anomalies in the mid-latitudes, due to either global warming or other mechanisms of climate change, would influence the frequency of low fuel moisture conditions associated with large areas burned.

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