CHAPTER 10

Climate, Weather, and Area Burned

M. D. FLANNIGAN
Canadian Forest Service, Edmonton, Alberta, Canada

B. M. WOTTON
Canadian Forest Service, Sault Ste. Marie, Ontario, Canada

I. INTRODUCTION

Forest fires are strongly linked to weather and climate (Flannigan and Harrington, 1988; Johnson, 1992; Swetnam, 1993). Fire has been an integral ecological process since the arrival of vegetation on the landscape. For the purposes of this chapter, we will define weather as short-term processes that result in variations in the atmospheric conditions ranging from minutes to a fire season. Processes that influence the atmosphere over time periods longer than a fire season will be defined as climate. There are several factors that control the climate and weather at any one location. These factors include variations in solar radiation due to latitude, distribution of continents and oceans, atmospheric pressure and wind systems, ocean currents, major terrain features, proximity to water bodies, and local features including topography (see Trewartha and Horn, 1980, for more details). As climate varies, the corresponding weather variables can vary in magnitude and direction.

The objective of this chapter is to highlight the connection between climate/weather and the area burned by forest fires. We have used examples primarily from Canada or North America to illustrate our points. This chapter is divided into sections that describe the relationships between surface weather and area burned, upper air features and area burned, and teleconnections and area burned. We also try to identify key knowledge gaps in the fire and weather/climate relationship. This chapter closes with a short discussion on how global change might influence forest fire activity and area burned in the 21st century.

II. WEATHER AND AREA BURNED—SYNOPTIC SURFACE FEATURES

The day-to-day weather can dramatically influence fire behavior and area burned. In fact, much of the area burned in a region during any given year occurs on just a few days of severe fire weather (Nimchuk, 1983; Harvey *et al.*, 1986). This has led to many studies over various spatial and temporal scales that try to relate the weather to fire. These studies can be broken into two broad categories, namely, case studies and what we will call area burned studies for the purpose of this paper. Case studies examine the conditions associated with an individual fire or an outbreak of fires and usually cover a short period of time and a relatively small area (approximately the fire area). Area-burned studies relate the weather to the area burned from numerous fires over many years. These area-burned studies have spatial domain ranges from hundreds of square kilometers to continental scale and a temporal range of 10 years to about 100 years. The temporal scale is often limited by the availability of area-burned data and meteorological data. This section will address both case studies and area-burned studies. In some studies the area burned is related to indexes such as components of fire danger rating systems or drought that are derived from meteorological data.

There have been numerous case studies that address the weather associated with a fire or an outbreak of fires. Most case studies have documented the weather prior to and during major fire runs (Stocks and Walker, 1973; Stocks, 1975; Quintilio *et al.*, 1977; Flannigan and Harrington, 1987; Hirsch and Flannigan, 1990). These studies have shown that fires spread rapidly when the fuels were dry and the weather conditions were warm to hot, dry, and windy. Turner (1970) studied the effect of hours of sunshine on fire season severity. The synoptic weather types associated with critical fire weather were studied by Schroeder (1964). These studies by themselves have limited application because of the narrow scope in terms of temporal and spatial scales used. However, they are of value in terms of identifying the most likely meteorological predictors of area burned that can be used in studies with a larger time and space domain (area-burned studies).

The most important elements of surface weather with respect to area burned are cold frontal passage, dry spells, and low relative humidities. These last two elements influence fuel moisture and the associated fire danger components which were also found to be important in terms of area-burned activity. Brotak and Reifsnyder (1977a) studied the synoptic weather conditions associated with large wildland fires (over 2000 ha) over the eastern half of the United States for the 1963–1973 period. They found that nearly 80% of these fires were associated with a cold front, either prior to or following passage of a dry cold front (Figure 1). It is important to note that a surface wind shift from southwest to northwest occurs with the passage of a cold front in the northern hemisphere. This is important because the flank of a fire with a southwest wind, which would typically be an ellipse in a SW-NE direction, would now become the head of the fire with a northwest wind which can cause rapid and significant growth in the fire. Haines *et al.* (1983) used over 2500 wildfires from the northeastern United States to examine the capability of the U.S. National Fire-Danger Rating System (NFDRS) to predict four measures of fire occurrence: the probability of a fire day, the number of fires per fire day, the number of fires per day, and the probability of a large-fire day. Good fits were found for the probability of a fire day and for the number of fires per fire day, whereas significantly poorer results were obtained for number of fires per day and the probability of a large fire day.

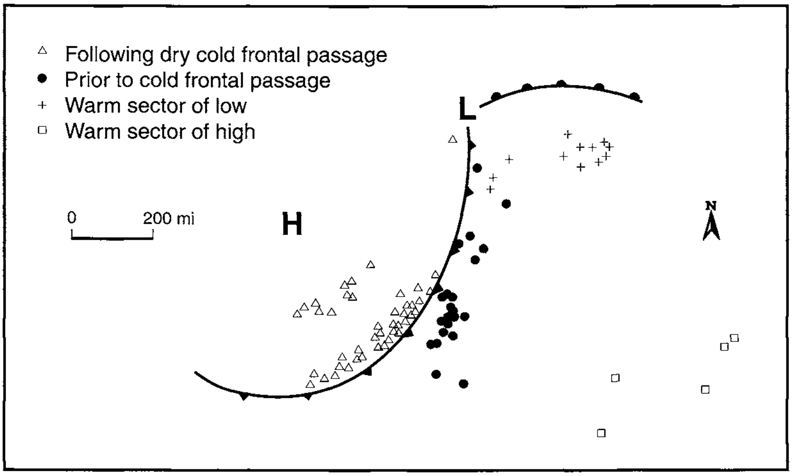

FIGURE 1 Idealized surface map showing relative position of major fires over eastern United States (from Brotak and Reifsnyder, 1977a).

Harrington *et al.* (1983) related the monthly provincial area burned in Canada to components of the Canadian Fire Weather Index (FWI) System for 1953–1980. They used mean and extreme values of components of the FWI System calculated at 41 stations across Canada. Results showed that the monthly means and extreme maximum values of the Duff Moisture Code (DMC—a model of the moisture content in the upper portion of the organic layers of the forest floor) and the Daily Severity Rating (DSR) were the best predictors of area burned. In western Canada, with the exception of the Yukon and Northwest Territories, the explained variance (r^2) averaged 33%. In the Territories and eastern Canada, the explained variance averaged 12%. Using the same data set, Flannigan and Harrington (1988) studied the relation between meteorological variables and monthly area burned by wildfire from May to August 1953–1980 for nine provincial-sized regions in Canada. They found that severe fire months were independent of rainfall amount but significantly dependent on rainfall frequency, temperature, and relative humidity. Results were similar to those obtained by Harrington *et al.* (1983) except that the meteorological variables did better in the Northwest Territories and eastern Canada than the Canadian FWI System (Van Wagner, 1987). The most important predictors were long sequences of days with less than 1.5 mm of rain and long sequences of days with relative humidity below 60%. These long sequences were assumed to be associated with blocking highs in the upper atmosphere.

The long-term average of area burned across a landscape is determined by a complex set of variables including the size of the sample area, the period under consideration, the extent of the forest, the topography, fragmentation of the landscape (rivers, lakes, roads, agricultural land), fuel characteristics, season, latitude, fire suppression policies and priorities, fire control, organizational size and efficiency, fire site accessibility, ignitions (people and lightning), simultaneous fires, and the weather. Thus results that explain 30% of the variance over large portions of the boreal forest are considered statistically significant.

III. WEATHER AND AREA BURNED—UPPER AIR FEATURES

How do upper air features influence forest fires at the Earth's surface? There are two ways that the upper atmosphere relates to forest fire activity. First, the weather observed at the Earth's surface is a strong indicator of what is happening in the three-dimensional atmosphere. Temperature, precipitation, wind, cloudiness, and atmospheric pressure depend largely on the horizontal and vertical state of the atmosphere. The strength, location, and movement of surface highs and lows and associated warm/cold fronts are functions of the three-dimensional atmosphere. Thus surface weather conditions at the fire site are greatly influenced by upper air features. Second, many large forest fires are not constrained to the surface in that these fires may have convection columns that extend many kilometers into the atmosphere. The interaction between the convection column and the vertical structure of the atmosphere can have a significant impact on fire behavior and fire growth (see Chapter 8 in this book).

There are two aspects of this section of relating upper air features to area burned. The first aspect uses the atmospheric circulation at a specified pressure level above the Earth's surface, typically the 500-mb level, and relates patterns in the atmospheric flow to area burned by wildfires. The term *long wave* is used with respect to the atmospheric circulation to denote northward or southward displacements in the major belt of westerlies characterized by large wavelength and significant amplitude, also known as planetary or Rossby waves. Typically, three to five long waves can be found encircling the northern hemisphere at any given time. The second aspect relates to the vertical structure of the atmosphere and relates this structure to area burned by fire. Vertical profiles of temperature, atmospheric moisture, and wind speed are commonly used in studies relating atmospheric structure with area burned.

A. Upper Air—Circulation

Upper atmospheric ridging is critical in terms of area burned. Newark (1975) was among the first to notice that forest fire occurrence in northwestern Ontario during the summer of 1974 was related to 500-mb-long wave ridging. Nimchuk (1983) related two episodes of catastrophic burning during the Alberta 1981 fire season to the breakdown of the upper ridge over Alberta. These episodes, which lasted 8 days, accounted for about 1,000,000 ha burned. The breakdown of these upper ridges is often accompanied by increased lightning activity as upper disturbances (short waves) move along the west side of the ridge. Additionally, as the ridge breaks down, strong and gusty surface winds are common. The ridge breakdown is preceded by warm and dry conditions associated with the upper ridge, which dries the forest fuels. These upper ridges can persist for weeks to months (Daley, 1991). Brotak and Reifsnyder (1977a) also studied the upper air conditions associated with 52 major wildland fires (area burned 2000 ha or more) in the eastern United States during the 1963–1973 period. They found that the vast majority of the fires were associated with the eastern portion of a small but intense short wave trough at 500 mb (Figure 2). Despite the difference in geographical location, the studies by Brotak and Reifsnyder (1977a) and Nimchuk (1983) may be discussing the same situation, although the emphasis changes from trough to ridge breakdown from the former to the latter. Cold fronts are often associated with the breakdown of

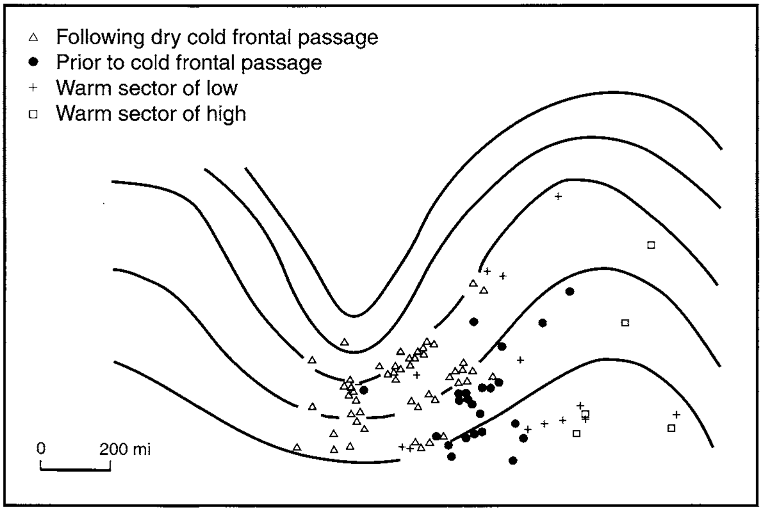

FIGURE 2 Idealized 500-mb map showing relative position of major fires over eastern United States (from Brotak and Reifsnyder, 1977a).

the ridge or the passing of a short-wave trough, which are also important in terms of major wildland fires (Brotak and Reifsnyder, 1977a).

Some researchers have used height anomalies in the upper atmosphere to address the relationship between long waves and area burned. Flannigan and Harrington (1988) found that the monthly 700-mb height anomaly for the forested regions of their provincial areas was the predictor that was selected the most when relating meteorological variables to monthly provincial area burned in Canada 1953–1980. The 700-mb height anomaly is calculated by subtracting the climatological average 700-mb height, typically a 30-year average, from the observed 700-mb height. Positive anomalies mean that the observed heights are higher than average, and, conversely, negative anomalies mean observed heights are lower than average. The height of the pressure level is a function of the air column's temperature, with lower heights generally related to lower temperatures and higher heights to warmer temperatures in the total air column from the surface to the specified pressure level. More recently, some studies have related height anomalies and blocking ridges to teleconnection patterns between North America and the surrounding oceans. Johnson and Wowchuk (1993) found that midtropospheric positive height anomalies (blocking ridges) were related to large-fire years in the southern Canadian Rocky Mountains whereas negative anomalies were related to small-fire years. They observed that these blocking ridges associated with the large-fire years were teleconnected (spatially and temporally correlated with respect to 500-mb heights) to upper-level troughs in the North Pacific and eastern North America, which is the positive mode of the Pacific North America (PNA) pattern (see teleconnection section). Skinner *et al.* (1999) found that 500-mb height anomalies were well correlated with seasonal area burned over various large regions of Canada. They also found a structure similar to the PNA pattern for the extreme fire seasons in western and west-central Canada. Current research suggests that blocking frequency is related to the wave number (the number of long waves in the westerlies—typically three to five) with blocking ridges being more frequent with higher wave numbers (Weeks *et al.*, 1997).

B. Vertical Structure of the Atmosphere

Fires can be divided into two groups: convection-column driven and wind driven (Nelson and Adkins, 1988; Nelson, 1993). Fires in which the convection column is well developed are more sensitive to the atmospheric lapse rate because these columns extend farther up into the atmosphere. The lapse rate is the rate of temperature change with height above ground. Typically, temperature decreases with height above ground in the lower atmosphere. Inversions denote those situations where temperature increases with increasing altitude. Wind-driven fires are influenced by strong winds at the surface and typically have significant vertical wind shear. Wind shear is the rapid change of speed and/or direction in any direction; typically there is a significant increase of wind speed with height above the ground as friction reduces the wind speed near the Earth's surface. Under such conditions, the convection column is sheared and, as such, does not play a significant role in fire spread and behavior. Additionally, there is a dynamic interaction between the fire and the atmosphere which can lead to some erratic fire behavior (see Chapter 8 in this book) such as fire whirls, horizontal roll vortices, spotting, and the development of pyrocumulus including thunderstorms generated by the fire (Stocks and Flannigan, 1987).

The vertical structure of the atmosphere influences fire behavior. Dry and unstable air enhances the growth of forest fires in two ways: first, in the absence of strong winds, it promotes a well-developed convection column, which may produce spotting and other erratic fire behavior like fire whirls; second, when wind speeds are strong near the Earth's surface, the instability allows these high winds to be mixed down to the surface, promoting fire spread and erratic fire behavior like horizontal roll vortices (Haines, 1982). An unstable lower atmosphere was a common feature of the large fires that Brotak and Reifsnyder (1977b) studied.

To address the role of the vertical structure of the atmosphere on fire activity, Haines (1988) developed a lower atmosphere severity index (LASI) for wildland fires to account for the influence of temperature stability and moisture content in the lower atmosphere. Unstable air is a layer of air that is characterized by a vertical temperature gradient such that air parcels displaced upward will accelerate upward and away from their original altitude. Haines found that only 6% of all fire season days fell into the high-index class for the western United States. However, 45% of days with large and/or erratic wildfire occurred during those high-index class days. Potter (1995) conducted a regional analysis of the LASI in the United States and suggested that the Haines LASI might be modified to improve performance in the southeastern United States. Werth and Ochoa (1993) used the LASI to evaluate the growth of two forest fires in Idaho. The LASI performed well at determining the time of the most explosive fire growth. Brotak (1993) explored whether the LASI could be used in a predictive sense by using early morning data (1200 GMT). His preliminary results suggested that the LASI calculated using early morning data does not work well in predicting the fire behavior for that afternoon.

The role of atmospheric stability and vertical moisture profile is a critical aspect for fire growth. Potter (1996) examined atmospheric properties associated with large wildfires (over 400 ha) in the United States from 1971 to 1984. He compared the lower atmosphere moisture, temperature, wind, and lapse rate for the 339 large fires in the data set with climatology using the same 14-year period. The results showed that the fire-day surface air temperature and moisture variables (dewpoint depression and relative humidity) at 0000 UTC (Universal Time Coordinated) differed significantly from climatological averages of these variables. There was no difference in wind shear between fire days and climatology days. Results from wind speed and lapse rate were inconclusive for this study. Garcia Diez *et al.* (1993) found that the stability and the saturation deficit of the lower atmosphere were related to the number of fires occurring in the following 24 hours in Galicia (Spain). Delgado Martín *et al.* (1997) defined four types of days based on stability and moisture levels: dry and unstable, moist and unstable, dry and stable, and moist and stable. They found for northwestern Spain that these four types of days and their associated fire risk were related to area burned, with dry and unstable days having the highest fire risk. Additionally, they suggested that days with a high number of fires are also those that contribute to more burned area.

Future research relating all components of the weather (surface and upper air features) should be pursued using a more rigorous spatial approach. For example, using relatively high-resolution (approx. 50–100 km) gridded area burned data in the analysis along with finer temporal resolution could yield a better understanding of the role of weather in area burned and provide insight into the relationship between surface weather and upper air features from an area-burned perspective. If or when better relationships between weather and area burned are obtained, it might be possible to predict area burned for a season as seasonal climate prediction is beginning to show potential (Uppenbrink, 1997).

IV. TELECONNECTIONS

Teleconnections are significant temporal correlations between meteorological variables in widely separated points on the globe. Over the past 100 years of meteorological study, a number of these correlations have been observed between various points. Perhaps the most well-known source of teleconnections is the Southern Oscillation (SO) in the equatorial Pacific Ocean or more specifically the part of this oscillation known as El Niño (ENSO). El Niño is characterized by a strong warming of sea surface temperature in the eastern and central equatorial Pacific Ocean and is accompanied by a weakening of trade winds in this region. It occurs at irregular intervals from 2 to 7 years, though its average return period is about 3 or 4 years. During an El Niño (or warm phase of the Southern Oscillation) there is typically an area of high pressure over the tropical western Pacific and unusually low pressure in the southeastern Pacific near the coast of South America. The opposite phase of the Southern Oscillation, sometimes known as La Niña, is characterized by higher surface pressures in the eastern Pacific and cooler sea surface temperatures along the equator.

The direct effects of this persistent weather pattern are quite evident in the equatorial Pacific. For hundreds of years, the inhabitants of Peru have seen El Niño's recurrence marked with widespread fish mortality along their coast and increased rainfall and widespread flooding. In Australia, El Niño events tend to bring severe drought across large areas of the eastern part of the continent. The resulting forest fire situations can be severe as was the case during the 1982/83 El Niño and the losses in forested land and life from the "Ash Wednesday" fires (Pyne, 1991). The drought and consequent severe wildfire situation in Indonesia in 1997 were also a result of the disruption of normal monsoon rains by this phenomenon.

Effects of this widespread warming of the ocean are not limited however to the central and western Pacific. There has been a great deal of research into teleconnections of El Niño and weather patterns farther abroad (Kiladis and Diaz, 1989). Correlations have been found between El Niño occurrence and hurricane activity in the Atlantic (O'Brien *et al.*, 1996) as well as drought occurrence in regions of Africa (Bekele, 1997). Much work has been done looking for ENSO teleconnections with weather patterns on the continent of North America as well. Horel and Wallace (1981) showed that warm waters of the equatorial Pacific were well correlated with positive 700-mb height anomalies over western Canada and 700-mb height anomalies in the eastern United States. Bunkers *et al.*'s (1996) study showed significant correlations between El Niño events and increased summer precipitation in the northern plains of the United States. The opposite correlation held for La Niña events. Shabbar and Khandekar (1996) and Shabbar *et al.* (1997) described precipitation and temperature patterns across Canada associated with the Southern Oscillation and suggested that the significant correlations they found could be used as a long-range forecasting technique particularly for the winter season. Such forecasting of temperature and precipitation anomalies would be of importance to fire managers as these are two important factors in estimating fuel moisture levels and the consequent levels of forest fire potential.

Studies of fire occurrence in association with El Niño and La Niña events have been carried out as well. Simard *et al.* (1985) divided the United States into five regions and correlated fire occurrence and area burned per year in each of these regions with a relative El Niño intensity index using about 73 years of historical fire data. Their results imply that any relation between fire activity and El Niño occurrence in the continental United States will be regional in character. They found a significant correlation between El Niño occurrence and decreased fire activity in the southern states. However, no other statistically significant relationships could be found. Swetnam and Betancourt (1990) used fire scars, tree growth chronologies, and fire statistics from Arizona and New Mexico and correlated these with the Southern Oscillation Index (SOI). The SOI is defined as the normalized difference in surface pressure between Tahiti, French Polynesia, and Darwin, Australia. The SOI or its anomaly is often used as an index of the strength and duration of El Niño and La Niña events. Positive SOI values indicate a higher pressure in the eastern Pacific and, as such, a La Niña event. Low SOI values indicate a lower pressure difference and an El Niño event. Swetnam and Betancourt found that in Arizona and New Mexico large areas burn after La Niña events and smaller areas burn after El Niño events. This corresponded to drier and wetter springs in the American southwest associated with La Niña and El Niño events, respectively. Brenner (1991) studied fire occurrence and area burned in Florida from 1950 to 1989. He found that a higher than average area burned in La Niña years and a lower than average area burned during El Niño years. It is interesting to note that in this study the highest correlations he found against area burned in Florida were with sea surface temperature anomalies from the central Pacific. This is perhaps not surprising as one would expect continental North America to be more strongly influenced by North Pacific atmospheric circulations than those in the tropics. The potential for North Pacific teleconnections with North American climate and fire activity will be discussed later in this section.

The temperature and precipitation teleconnection studies of Shabbar and Khandekar (1996) and Shabbar *et al.* (1997) suggest that a Southern Oscillation signal might be detectable in Canada. They show significant decreases in winter precipitation across the lower prairies and British Columbia and increases in the Northwest Territories during El Niño years. La Niña years have a corresponding increase in winter precipitation across the prairies. One might presume that the area burned during the fire season following such an El Niño or La Niña winter precipitation anomaly might demonstrate some positive or nega-

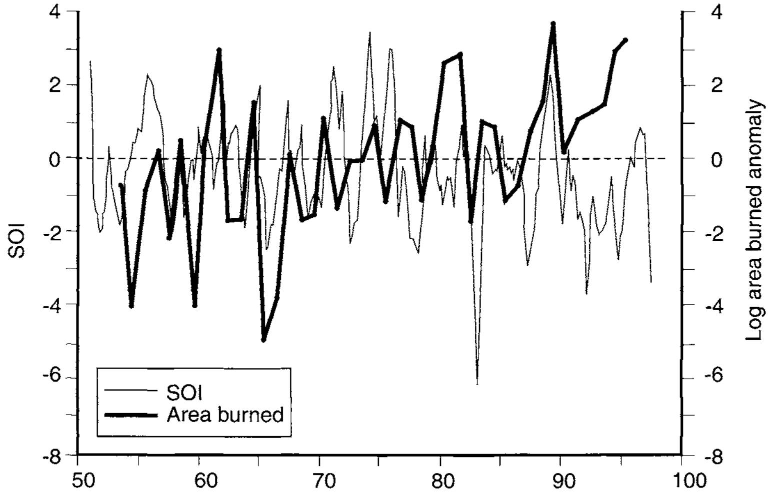

FIGURE 3 Southern Oscillation Index (SOI) and central Canada normalized area-burned anomaly for 1953 to 1995.

tive correlation, respectively. Figure 3 shows normalized area burned anomaly in central Canada plotted with smoothed monthly SOI values from 1953 to 1996. There appears, in this graph, to be no strong correlations (negative or positive) for this period. Correlation of winter levels of SOI and following summers area burned also yields no significant relationship.

Although some correlations have been found between the Southern Oscillation and fire occurrence in North America, the relative lack of signal might not be surprising since El Niño events tend to be strongest in the North American winter months and typically weaken or disappear as summer (and the fire season) approach. Indeed the correlation studies of Shabbar and Khandekar (1996) and Shabbar *et al.* (1997) show that links between ENSO and Canadian precipitation and temperature are strongest in the winter months. However, recent research by Bonsal and Lawford (1999) found a relationship between El Niño and La Niña events and summer extended dry spells on the Canadian prairies.

The results of Brenner (1991) suggest there may be some value in looking at North Pacific sea surface temperatures for teleconnection not just with North American climate but with fire activity. A number of studies have shown a correlation between North Pacific sea surface temperatures and El Niño events (Reynolds and Rasmusson, 1983; Trenberth, 1990; Deser and Blackmon, 1995). Studies of the North Pacific have shown Southern Oscillation-like variability in the sea surface temperature pattern, which imply that a similar North Pacific Oscillation (NPO) exists (Tanimoto *et al.*, 1993; Trenberth and Hurrell 1993;

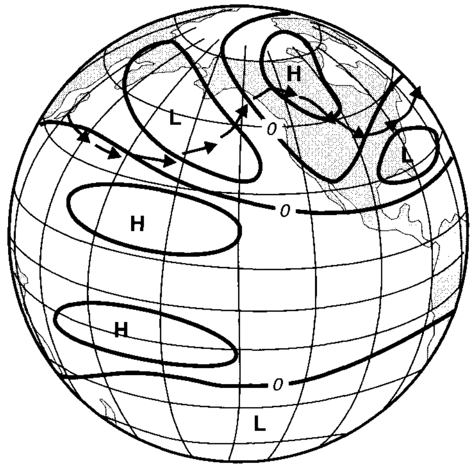

FIGURE 4 Map showing the geopotential height anomalies associated with the positive mode of the PNA teleconnection (from Horel and Wallace, 1981). The arrows depict the midtropospheric streamline as distorted by the anomaly pattern. The negative mode of the PNA has the anomalies with an opposite sign; that is, the low-high-low anomaly sequence (North Pacific-western Canada-southeast United States) of the positive mode switches to high-low-high anomaly sequence for the PNA negative mode.

Zhang *et al.*, 1997). A teleconnection has, in fact, been identified between the North Pacific and North America. Known as the Pacific North American (PNA) teleconnection (Figure 4), it is really a triple connection between an anticyclonic circulation over the North Pacific, a cyclonic circulation over western Canada, and a second anticyclonic circulation over the southeastern United States. Walsh and Richman (1981) found a signature of this triple teleconnection when they used 31 years of North Pacific sea surface temperature data and U.S. temperature data to show regional correlations. Their sea surface temperature data correlated well with air temperature fluctuations over the far western states and the southeastern states but with opposite signs in the two regions. This work also suggested that such correlations could potentially be used for seasonal predictability in some areas. Johnson and Wowchuk (1993) found a signature of the PNA triple teleconnection during a study of 35 years of area-burned data in the southern Canadian Rocky Mountains. They found that, during large-fire years, surface blocking high-pressure systems in their study area were correlated with upper level troughs in the North Pacific and in eastern North America. Skinner *et al.* (1999) found strong correlations between area burned in a number of large regions in Canada and the presence of strong 500-mb-level ridging. During extremely high years of area burned, the PNA teleconnection pattern was evident with significant correlations between the 500-mb values at the three "triplet" locations.

Teleconnections from sea surface temperatures such as the Pacific North America pattern and those from the Southern Oscillation result from complex ocean–atmosphere forcing coupled with large-scale atmospheric circulations. Climate modeling with coupled atmosphere/ocean models has shown that tropical flow patterns and consequent rainfall show little sensitivity to initial conditions of the atmosphere but are determined mainly by boundary conditions of sea surface temperature in the model (Shukla, 1998). The details of these teleconnections are not as important to us in the context of this chapter as the fact that the relatively high temporal variability of weather parameters over land masses can be shown to be correlated with the more slowly varying oceans. Weather prediction limits based on the intrinsic variability in the atmosphere are thought to be on the order of 2 weeks. However, ocean variability occurs on a much slower time scale, and, as such, teleconnections imply that seasonal climate prediction may be possible (Uppenbrink, 1997). The use of such teleconnections as long-range forecasting tools has great appeal to all those involved in the fire business. Recent research has shown that the phase of the North Pacific Oscillation has a great influence on climate anomalies in North America during the Southern Oscillation (Gershunov *et al.*, 1999). They found correlations between the Southern Oscillation and Pacific sea surface temperatures and precipitation anomalies in North America to be much stronger during the high phase of the North Pacific Oscillation. This has strong implications for longer term predictions of North America's weather and climate as the North Pacific Oscillation varies with a 50–70-year time period (Minobe, 1997). Being able to plan a fire season's activity during the winter before, based on current sea surface temperature levels, could potentially allow fire management agencies greater efficiency in allocating resources. Indeed, coupled atmosphere/ocean modeling of the strong El Niño in 1997–1998 has shown very good results in predicting several months in advance seasonal precipitation anomalies in North America (Kerr, 1998). However, predicting fire activity is a difficult task. Forest fire occurrence and area burned tend to have a strong dependence on shorter term local weather, particularly dry spells and wind events, than they do on longer term conditions. Certainly, while an exceptionally dry or warm winter would seem to indicate a potential for much drier fuels for the upcoming fire season, small-scale synoptic events such as showers or thunderstorms tend to drive day-to-day fire potential. However, the correlations already found between area burned and the Southern Oscillation and Pacific Ocean sea surface temperatures show there is potential, with further analysis, that these teleconnections can be used to predict qualitatively the fire severity potential of the upcoming fire season. Preliminary results from Flannigan *et al.* (2000) show

TABLE 1 Maximum Correlation between Pacific SSTs and Seasonal Provincial Area Burned 1953–1976 and 1977–1995[a]

Province	1953–1976	1977–1995
BC	0.53 16°S 106°E	−0.52 20°N 102°W
Yukon/NWT	0.64 20°S 178°E	0.68 20°N 122°E
Alberta	−0.72 36°N 142°W	0.55 0°N 162°E
Sask.	0.51 16°N 166°W	−0.55 12°S 162°E
Man.	0.61 24°N 174°W	0.60 12°N 130°E
W. Ont.	−0.70 4°N 150°W	0.59 4°N 118°W
E. Ont.	−0.70 20°N 134°W	0.64 4°S 146°E
Que.	−0.72 4°N 102°W	0.62 20°S 106°E

[a]The location of the maximum correlation is displayed as well.

significant correlations between the winter season sea surface temperature (Jan.–Apr.) and provincial seasonal area burned (May–Aug.) in Canada by segregating the analysis by North Pacific Oscillation phase (Table 1). Figures 5 and 6 show the relationship between the seasonal area burned in eastern Ontario and the lagged (Jan.–Apr.) sea surface temperature anomaly for the 1977–

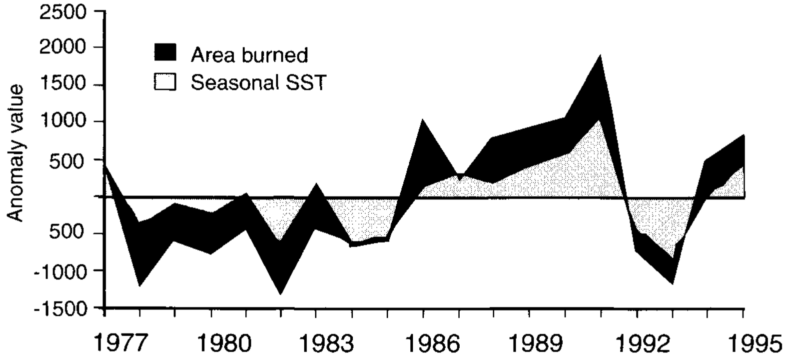

FIGURE 5 Normalized seasonal area burned in Eastern Ontario and lagged (Jan.–Apr.) SST anomaly for 1977–1995.

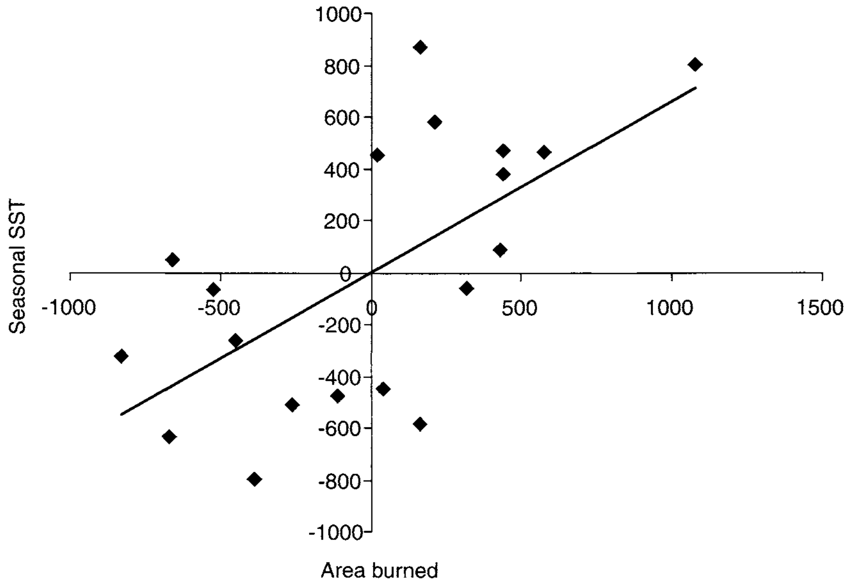

FIGURE 6 Normalized SST anomaly (Jan.–Apr.) versus normalized seasonal area burned for eastern Ontario 1977–1995.

1995 period with a time series and a scatter plot. The correlation is .64 (see Table 1) which explains about 41% of the variation in the data.

V. FUTURE WARMING AND AREA BURNED

There is consensus in the scientific community that human activities are responsible for recent changes in the climate (Intergovernmental Panel on Climate Change, IPCC, 1996). Specifically, increases in radiatively active gases such as carbon dioxide, methane, and the chlorofluorocarbons in the atmosphere are causing a significant warming of the Earth's surface. Significant increases in temperature are anticipated in the next century and are projected to occur rapidly.

There are many General Circulation Models (GCMs) that enable researchers to simulate the future climate. These models are three-dimensional representations of the atmosphere, ocean, cryosphere, and land surface. Transient simulations are available from GCMs which allow examination of the possible rates of change in the climate. Also, recent GCM simulations include sulfate aerosols. The major areas of uncertainty in GCMs include clouds and their radiative effects, the hydrological balance over land surfaces, and the heat flux at the ocean surface (IPCC, 1996). Despite these uncertainties, the GCMs provide the best means available to estimate the impact of changes in the future climate on the fire regime at larger scales. Most models agree in predicting the greatest warming at high latitudes in winter. Confidence is lower for estimates of precipitation fields, but many models suggest an increased moisture deficit particularly in the center of continents during summer. In addition to temperature, other weather variables will be altered in a changed climate such as precipitation, wind, and cloudiness. The variability of extreme events may also be altered (Mearns *et al.*, 1989; Solomon and Leemans, 1997). Some studies suggest universal increases in fire frequency with climatic warming (Overpeck *et al.*, 1990; IPCC, 1996). The universality of these results is questionable because an individual fire is a result of the complex set of interactions that include ignition agents, fuel conditions, topography, and weather including temperature, relative humidity, wind velocity, and the amount and frequency of precipitation. Increasing temperature alone does not necessarily translate into greater fire disturbance.

Flannigan and Van Wagner (1991) compared seasonal fire severity rating values (SSR—a component of the Canadian Forest Fire Weather Index System) from a $2xCO_2$ scenario (mid-21st century) versus the $1xCO_2$ scenario (approx. present day) across Canada. Their study used monthly anomalies from three GCMs (Geophysical Fluid Dynamics Laboratory, GFDL; Goddard Institute for Space Studies, GISS; and Oregon State University, OSU). The results suggest increases in the SSR all across Canada with an average increase of nearly 50%, which might translate roughly into an increase of area burned by 50%. Stocks *et al.* (1998) used monthly data from four GCMs to examine climate change and forest fire potential in Russian and Canadian boreal forests. Forecast seasonal fire weather severity was similar for the four GCMs, indicating large increases in the areal extent of extreme fire danger in both countries under a $2xCO_2$ scenario. Stocks *et al.* (1998) also conducted a monthly analysis using the Canadian GCM, which showed an earlier start to the fire season and significant increases in the area experiencing high to extreme fire danger in both Canada and Russia, particularly during June and July. Flannigan *et al.* (1998a) used daily output from the Canadian GCM to model the Fire Weather Index for both the $1xCO_2$ and $2xCO_2$ scenarios for North America and Europe. The FWI represents the intensity of fire as energy output per unit length of fire front. Figure 7 shows the ratio of the $2xCO_2$ to $1xCO_2$ values for both mean FWI and maximum FWI for the 9 years of simulation for North America and Europe. There is a great deal of regional variation between areas where FWI decreases in a $2xCO_2$ scenario (values below 1.00) to areas where the FWI increases greatly in the warmer climate. Much of eastern Canada and northwestern Canada have ratios below 1.00, indicating that the FWI decreases despite the warmer tem-

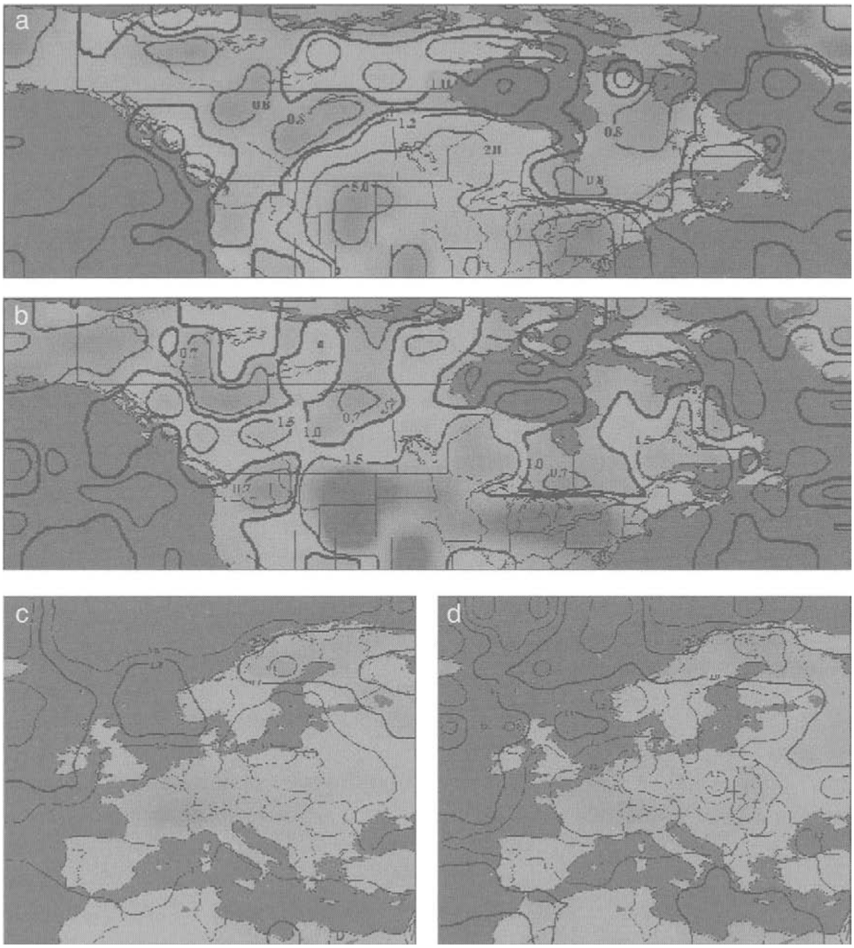

FIGURE 7 Mean and maximum FWI ratios ($2xCO_2/1xCO_2$) for North America (a, b) and Europe (c, d) (Flannigan *et al.*, 1998a).

peratures associated with a $2xCO_2$ climate. Noteworthy is the area of decreased FWI over western and northwestern sections of Canada where historically large portions of the landscape have been burned. However, due to the coarse spatial resolution of the GCM (approx. 400 km), confidence in the results over complex terrain like mountainous areas is low. In such areas, a Regional Climate Model (RCM) should be used (Caya *et al.*, 1995) where the finer spatial resolution (~40 km) can better resolve mountain ranges, and so on. Significant increases in the FWI are evident over parts of central North America. The ratio of extreme maximum values of the FWI for the 9-year period show a similar pattern, with higher ratios over central continental areas and lower values over portions of eastern Canada. On the other hand, there are increases in the maximum FWI over portions of western Canada. Over northern Europe, Figure 7 shows increased mean FWIs over the southern half of Sweden and extreme southeastern Finland for warmer conditions, whereas the remainder of northern Europe shows decreased mean FWIs. Interestingly, according to the simulations, fire danger will decrease in the northern sections of northern Europe where traditionally forest fires have been large and frequent, and fire danger will increase over southern Sweden where forest fires are not normally severe. Results for maximum FWIs show a similar pattern when compared with the mean FWIs, with the exception of southern Norway where FWIs increased. Consequences of climate change on fire disturbance must be viewed in a spatially dependent context.

Flannigan *et al.* (1998a) suggest that the reason for the decreased FWI despite the increasing temperature is due primarily to changes in the precipitation regime and, in particular, to increases in precipitation frequency. These model results (Figure 7) are in good agreement with recent fire history studies (~ the last 200 years) (Flannigan *et al.* 1998a), many of which show decreasing fire activity despite the warming since the end of the Little Ice Age (~1850). These modeled results are also consistent with the modeled fire weather and charcoal record anomalies for a warm period during the mid-Holocence about 6000 years BP, which was about 1°C warmer than present for Canada (Flannigan *et al.*, 1998b).

Other factors such as ignition agents, length of the fire season, and fire management policies may greatly influence the impact of climate change on the fire regime. Ignition probabilities may increase in a warming world due to increased cloud-to-ground lightning discharges (Price and Rind, 1994). Price and Rind suggest that lightning-caused fires would increase by 44% and that the associated area burned would increase by 78% by the end of the 21st century, although they assume no changes in fuels, which may greatly influence the lightning ignitions and area burned. The longer fire season will begin earlier in the spring and extend longer into the autumn. Wotton and Flannigan (1993) estimated that the fire season length in Canada on average will increase by 22%, or 30 days in a $2xCO_2$ world. Fire management policies and effectiveness will continue to change. Also, research has suggested that the persistence of blocking ridges in the upper atmosphere will increase in a $2xCO_2$ climate (Lupo *et al.*, 1997), which could have a significant impact on forest fires as these upper ridges are associated with dry and warm conditions at the surface and are conducive to forest fires. These are all confounding effects that may dampen or amplify the impact of a changing climate on the fire regime.

Future work might include using the improved relationships between climate/weather and area burned to estimate what the fire regime will be like in the future. This would assist land managers with long-term planning. Also, predictions of future fire regimes are critical in terms of the carbon balance where changes in the natural disturbance regime like fires could be responsible for the boreal forest becoming a source of carbon rather than a sink (Solomon and Leemans, 1997).

The important aspect of the impact of climate change on forest fires with respect to the influence on vegetation is that fire may be more important than direct effects of climate change (Weber and Flannigan, 1997). Fire can act as an agent of change to hasten the modification of the vegetation landscape into a new equilibrium with the climate if species are able to migrate fast enough.

VI. SUMMARY

Weather is a critical factor in determining the timing and size of fires. We have seen in this chapter that dry, windy, and warm surface weather conditions are conducive to area burned. However, these surface weather conditions are a reflection of the synoptic weather pattern which is a function of the dynamics of the three-dimensional atmosphere. The breakdown of the upper blocking ridge is one pattern of the upper atmospheric circulation that is a common feature of significant area-burned events. These blocking ridges typically bring 7–10 days or longer periods of warm dry weather followed by windy conditions as the ridge deteriorates. The breakdown of the upper ridge is often associated with a cold front passage at the surface which has been shown to be a common factor of large fires. Additionally, because of some large-scale circulation patterns, there are significant relationships between the weather in widely separated points on the globe, and often these circulation patterns have a cyclical nature such that seasonal forecasts may be viable. Last, preliminary indications from climate-modeling work suggest that climate change may result in increased area burned for many regions of the world.

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