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Chapter 2

Climatic and Weather Factors Affecting Fire Occurrence and Behavior

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Abstract

Weather and climate have a profound influence on wildland fire ignition potential, fire behavior, and fire severity. Local weather and climate are affected by large-scale patterns of winds over the hemispheres that predispose wildland fuels to fire. The characteristics of wildland fuels, especially the moisture content, ultimately determine fire behavior and the impact of fire on the landscape. The physical processes related to combustion, fire, and plume behavior are largely affected by both daily weather and long-term climate.

2.1. Introduction

Both human-caused and lightning-caused fires result from changing climate and weather factors. After ignition, fire behavior is largely affected by ambient atmospheric factors including wind, atmospheric stability, fuel moisture, and topographic influences. In this chapter we will discuss the differences between climate and weather, how climate and weather affects fire, what the future implications may be for fire and climate change, and how the important atmospheric factors interact with fuel properties to determine fire behavior. In Section 2.2 we will discuss the impact of climate (climate anomalies, teleconnections and climate change) on fire and in Section 2.3 we will demonstrate the importance of weather (temperature, lightning, moisture and wind) on fire occurrence and fire behavior.

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2.2. Climate

This section provides an overview of climate and its effects on fire. Climate is defined by the variability in weather and results from numerous non-linear processes and interactions between the atmosphere, the hydrosphere, the biosphere, and the geosphere. Any change in one of these spheres affects the other realms and these linked changes eventually result in changes to fire behavior. It is unclear how future fire behavior will be affected with anticipated changes in climate but it is clear that extreme weather conditions occurring over sufficient time periods will affect the moisture content of wildland fuels and thus fire regime characteristics. Most research indicates that future global temperatures will be warmer than current levels and that drought areas will increase making wildfire activity more likely (IPCC, 2007).

2.2.1. Defining climate

The climate we associate with a particular area involves the entire range of weather conditions that together combine to produce what is considered normal or average for that location. Climate may be defined as the statistical properties of the atmosphere that include both the frequency and variability of weather events. Climate zones, such as those found in the Koeppen system (McKnight & Hess, 2000), link the world distribution of vegetation types to various combinations of monthly mean temperature and precipitation. Each climate zone is distinguished across Earth's surface relative to latitude, degree of continentality, and location relative to major topographic features. Wildland fuel type characteristics such as fuel loading, fuel volume, continuity, moisture content, and size and shape are intimately associated with various climate zones. Accordingly, fire regime characteristics such as fire frequency, fire intensity, and season of occurrence are largely defined by climate. Possible changes in climate will affect the characteristics of wildland fuels and fire regimes.

The ranges in climate, along with variations in vegetative conditions, produce differences in climate from one region to the next. In both the Northern and Southern Hemisphere, fire seasons commence in lower latitude regions and progress poleward as the warm season develops and as Earth continues its orbit about the sun. Annual changes in climatic features of a region, such as snowpack and spring snowmelt or the lengths of growing seasons, are all important considerations to the start and the length of fire seasons (Westerling et al., 2006).

2.2.2. Climate anomalies

The fire climate is a synthesis of daily fire weather conditions averaged over a long period of time. The range of weather conditions over time helps determine fire season characteristics along with the normal or expected conditions. Daily extremes in the climate record profoundly affect fire occurrence and fire behavior. It is widely regarded that large wildfires requiring significant suppression resources are associated with weather anomalies that act to shape the climate record. The majority of the area burned by wildfires, which may be underestimated in some regions (Soja et al., 2002), is frequently associated with a very small number of the observed fires each year and has been attributed to changing climate and increasing fuel hazards (Stephens, 2005).

Anomalies of temperature are experienced over days and may persist for seasons and are observed over large regions of continents. Precipitation deficits may be observed over similar time periods but often display more complex patterns due to the factors that contribute to the development of rain and snow. The near random distribution of warm season convective precipitation often leads to irregularities in spatial patterns of precipitation on short time scales. Over longer time scales, precipitation patterns may become more evident as reflected in areas of flooding and drought. Geographic nonuniformity in precipitation patterns frequently occurs over continents, which allows for a region to be dry adjacent to a region experiencing above-normal precipitation. At middle and high latitudes, the geographic nonuniformity is linked to the direction of the prevailing upper-atmospheric winds that govern the strength and direction of travel of storms.

Lack of moisture over an extended period of time may lead to drought. Droughts are associated with persistent departures of the large-scale weather pattern from its normal pattern. It is believed that ocean surface temperatures contribute to the persistent weather patterns that are associated with drought (Cayan et al., 1998; Herweijer et al., 2007; Seager et al., 2005; Ting & Wang, 1997). Droughts are also commonly linked to increased wildfire occurrence (Girardin et al., 2006; Swetnam & Betancourt, 1998) and to increased fire size (Maingi & Henry, 2007). Westerling et al. (2003) found that seasonal fire severity may be predicted with some skill based on moisture anomalies from antecedent seasons.

2.2.3. Teleconnections

Teleconnection is a term used to describe the tendency for atmospheric circulation patterns from one location on the globe to be related either directly or indirectly to another that spans a significantly large area. Teleconnections play a vital role in the study of air–sea interactions and global climate processes. They often prove useful in understanding climate patterns that occur across the world.

Probably the most well-known teleconnection is the El Niño Southern Oscillation (ENSO). It is a phenomenon with global teleconnections and is observed in the tropical Pacific Ocean in which there is either a cooling or warming from the average sea surface temperature (Bridgman & Oliver, 2006). The relationship between ENSO and climate include drought frequency in Africa (Bekele, 1997), upper-atmospheric height anomalies over western Canada and the eastern United States (Horel & Wallace, 1981), summer precipitation in the Northern Plains of the United States (Bunkers et al., 1996), and temperature and precipitation patterns observed across Canada (Shabbar et al., 1997). Simard et al. (1985) studied the relationship between ENSO and fire occurrence in the United States. Their results indicate a strong correlation between El Niño (the warm phase of ENSO) and decreased fire occurrence in the southern United States. However, the results from other areas of the United States were less robust and indicated that ENSO effects are probably best characterized as regional in scale. Hotter and drier conditions favoring increases in wildfire occurrence and behavior typically occur in Australia during El Niño years than occur in La Nina years (Power et al., 2006).

An important intraseasonal variation, known as the Madden Julian Oscillation, has a 30–60 day oscillation period and is dominant in the western Pacific. However, like the ENSO phenomenon, this oscillation is sometimes thought to have far-reaching global teleconnections and has been linked to adversely affecting the forecast skill of numerical models used to predict weather not only in the Tropics but also in the extratropics of the Northern Hemisphere (Hendon et al., 2000).

The northern and tropical Pacific Ocean likely contributes to weather patterns that affect fire occurrence and behavior. The North Pacific Oscillation (NPO) or Pacific Decadal Oscillation (PDO) is a long-lived phenomenon of cyclical changes in ocean temperatures that have a great influence on climate anomalies in North America. In fact, research indicates that there is a correlation between North Pacific sea surface temperatures and El Niño events (Deser & Blackmon, 1995; Reynolds & Rasmussen, 1983; Trenberth, 1990). Flannigan et al. (2000) showed that significant correlations exist between the winter season sea surface temperature and provincial seasonal area burned (May–August) in Canada by separating the analysis by NPO phase.

2.2.4. Climate change

There is a consensus in the scientific community that global warming is occurring and that human activities are responsible for at least some of the increase in temperatures. Whether the warming is originating from anthropogenic or natural causes, it appears that radiatively-active gases in the atmosphere, such as carbon dioxide and methane, are contributing to a warmer global climate. General Circulation Models (GCMs) are used by scientists to simulate the future climate. These models are three-dimensional characterizations of the atmosphere, land, and ocean surfaces that incorporate the uncertainties in the effects of clouds and their radiative effects, the hydrologic balance over land, and ocean heat flux rates. Most model projections indicate that the greatest observed warming will occur at high latitudes in winter. Most models also indicate greater moisture deficits, particularly in the center of continents, during summer. Notaro et al. (2007) have found that future climates will be warmer due mainly to the elevated levels of carbon dioxide. However, these researchers suggest a positive feedback on the climate system that involves disruptions in the hydrologic cycle due to decreased rates of evapotranspiration. The physiological effect from plants' lower evapotranspiration rates will produce drying in tropical climates but increased precipitation in high latitudes due to warming from the combined physiological (less evapotranspiration) and radiative effects. A poleward shift in the boreal forest is expected as both the radiative and physiological effects enhance vegetation growth in the northern tundra and the radiative effect induces drying and summertime heat stress on the central and southern boreal forest. Vegetation feedbacks substantially impact local temperature trends through changes in albedo and evapotranspiration. The physiological effect increases net biomass across most land areas, while the radiative effect results in an increase over the tundra and decrease over tropical forests and portions of the boreal forest.

Some studies indicate universal increases in fire frequency with climatic warming with perhaps significant regional changes in fire activity and area burned (Flannigan et al., 2005; IPCC, 1996; Overpeck et al., 1990; Tymstra et al., 2007). Other studies indicate uncertainty regarding future fire occurrence and behavior associated with the effects of future climate change. Beer and Williams (1994) found that fire activity in Australia is expected to increase but that models may be underpredicting relative humidity, which, in turn, may overestimate fire activity.

2.3. Weather

The meteorological variables relevant to affecting fire behavior result from synoptic scale forcing of weather occurring at the microscale where fire, weather, fuels, and topography interact. Diurnal changes in relative humidity, temperature, and wind speed and direction may dramatically influence fire behavior (Flannigan & Harrington, 1987; Hirsch & Flannigan, 1990). Atmospheric instability, normally computed daily by the Haines Index (Haines, 1988), extended dry spells, and cold front passages are other examples of weather conditions important to managing wildfires and maintaining safety for firefighters (Brotak & Reifsnyder, 1977; Johnson & Miyanishi, 2001). In addition, the electrical properties of clouds cause lightning that affects the ignition of forest fires (Latham & Williams, 2001; MacGorman & Rust, 1998).

2.3.1. Defining weather

Weather is defined as the state of the atmosphere at some place and time, described in terms of such quantitative variables as temperature, humidity, cloudiness, precipitation, and wind speed and direction. Weather is dynamic and differs from the climate of a location, since observed weather over a time period constitutes climate. Fire weather, collectively, is the weather variables, especially wind, temperature, relative humidity, and precipitation that influence fire starts, fire behavior, or fire suppression (Pyne et al., 1996). Kasischke et al. (2002) used geographic analyses to show that the most relevant weather factors affecting fire occurrence in Alaska were growing season temperature, precipitation, and lightning frequency. Short-term local weather, particularly unusual dry spells, low relative humidities, and windy weather generally associated with cold fronts, predispose wildland fuels to fire (Johnson & Miyanishi, 2001).

2.3.2. Temperature

The fraction of the incoming solar radiation that is not reflected from Earth's surface is absorbed and converted to heat. Temperature is the average kinetic energy or energy of motion exhibited by the atoms and molecules composing a substance and is important in determining the ease of combustion of wildland fuels. Heat, an important aspect of the fire triangle, is the energy transferred between an object of greater temperature to an object of lower temperature. It is this heat energy that is crucial in beginning the evaporative or preheating phase of combustion

(Johnson & Miyanishi, 2001). Therefore, higher temperatures heat forest fuels and predispose them to ignition provided that an adequate ignition source becomes readily available (lightning or some anthropogenic source). Ambient temperature undergoes a daily or diurnal cycle that allows for increased fire behavior during the warmest part of the day and less fire activity during the coolest part of the day.

Temperature inversions typically occur during nighttime and usually lead to a decrease in fire activity. Warmer air at some small distance above Earth's surface creates a stable environment such that the smoke-filled air is more dense than the surrounding air and thus spreads horizontally. Temperature inversions may, however, lead to the development of thermal belts whereby sloped valleys in contact with the warm stable layer of air burn more actively than do the cooler slopes either above or below the stable inversion layer.

An important aspect of temperature that relates to fire behavior is the horizontal and vertical distribution of temperature. Vertical temperature contrasts in the atmosphere are described by the degree of atmospheric stability. An unstable atmosphere is one that cools to some degree with increasing height from Earth's surface and can lead to thunderstorm or cloud development as air is allowed to move upward from the surface. Unstable air leads to increased fire behavior in two ways: first, it allows for a well-defined convective plume or column that may produce fire whirls and/or spotting; second, unstable air allows for stronger winds to mix down to the surface, which can lead to higher fire spread rates, and horizontal roll vortices (Haines, 1982). A Lower Atmospheric Stability Index (LASI) was developed (Haines, 1988) and then modified (Potter, 1995) to help determine the potential for wildfires to become large and/or erratic.

2.3.3. Lightning

Lightning contributes to wildfires worldwide but only leads to ignition when fuel type and fuel moisture are favorable. There is some debate as to whether the positive cloud-to-ground (CG) lightning strikes produce more ignitions than do their negatively charged counterpart. It is believed that most lightning-caused wildfires are caused by more energetic lightning strokes. Approximately 90% of CG lightning flashes worldwide transfer negative electric charge to the ground. These negative flashes tend to be multi-stroked compared to the 10% of CG flashes that transfer positive charge to the ground in single-stroke flashes. It is thought that single-stroke flashes allow for a longer continuing current and thus are more apt to cause fire initiation. Only approximately half of the negative flashes contain continuing currents (Uman, 1969). This commonly regarded method of fire initiation has been questioned, however, by Flannigan and Wotton (1991), who found large numbers of negative CG flashes with continuing currents.

Fuel type and fuel state are also important to the occurrence of wildfires. Latham and Williams (2001) found that some fuel types are more efficient in lightning-caused ignition, based on a 7-year study utilizing geographic information system (GIS) layers of fuel type with lightning occurrence. The study indicates that trees including both coniferous and deciduous (0.03–0.05 fires/flash) are more apt to ignite compared to grass, shrubs, and croplands (0.003–0.02 fires/flash). Lightning fire efficiency rates are dependent upon a multitude of factors that include synoptic weather conditions, fuel types, thunderstorm characteristics including rainfall and lightning rates, lightning characteristics, and fuel state that primarily describes the moisture content of fuels (Johnson & Miyanishi, 2001).

2.3.4. Moisture

Atmospheric moisture in the form of water vapor and precipitation plays a significant limiting factor on fire occurrence and fire behavior by affecting fuel moisture in both dead and living plants. Evidence suggests that increasing amounts of fuel moisture act to retard the rate of combustion, preheating of fuels, and ease of ignition. When the air is saturated, there exists an equilibrium between evaporation and condensation. Much of the time in areas that are prone to fire, evaporation is greater than condensation, and wildland fuels lose their moisture to the ambient air through the process of evapotranspiration. Ambient air evaporation rates are known to change based on the difference between the vapor pressure between the adjacent air and a water surface (Johnson & Miyanishi, 2001). Relative humidity refers to the amount of water vapor in the air at one time relative to the maximum amount of water vapor the air could hold at the same temperature. It undergoes a diurnal cycle linked to the normal rising and falling of the ambient temperature and dew point temperature.

Indirectly, existing moisture on Earth's surface that is in contact with the air is related to the ease of temperature changes. During times of moisture pooling or ponding, available energy from incoming solar radiation is used in evaporation. Otherwise, when surface moisture is scarce, the energy from incoming solar radiation is converted to heat. Precipitation varies widely in time and space in both hemispheres, and these patterns also exhibit seasonal shifts depending upon factors such as proximity to large bodies of water, prevailing upper-atmospheric wind patterns, and storm tracks.

2.3.5. Wind

Air moves in response to pressure differences in Earth's atmosphere and as a result of frictional effects near Earth's surface. Wind affects fire occurence and especially fire behavior at the synoptic, regional, and microclimate scales. Fast-moving air at high altitudes or the jet stream level has been observed to enhance wildland fire behavior by allowing drier and warmer stratospheric air to penetrate to the lower part of the troposphere (Carlson, 1980; Danielsen, 1968; Keyser & Shapiro, 1986). Regionally, both warm and cold surface fronts are linked to jet stream behavior and both create challenges for wildland fire management. Weather changes that occur on a daily basis from air mass changes can have a considerable impact on fire occurrence and fire size. Brotak and Reifsnyder (1977), studying the relationship between major fires in the eastern United States, found that nearly 80% of large fires were associated with a cold front, and were predominantly associated with the passage of dry cold fronts. Winds associated with cold fronts are also important to smoke dispersal from large fires (Freitas et al., 2005).

There are also a number of important local wind circulations that are observed on the microclimate scale. Sea breezes and land breezes, occurring both during the day and night respectively, result from pressure differences induced by the heating and cooling rate of the land compared to the ocean. Mountain and valley winds are also related to the relative diurnal heating of the valley and mountaintops.

Mountain winds can sometimes have devastating effects when air is forced to descend through narrow mountain passes. Not only does the wind speed become excessive, the descending air tends to warm adiabatically, resulting in warm, dry, and fire-prone conditions. Examples of such föhn winds include the Santa Ana in southern California, the Chinook in the lee of the U.S. Rocky Mountains, the Bergwind in South Africa, the Terral in Spain, and the Nor'wester in New Zealand (see Whiteman, 2000).

2.4. Fire, climate, and weather

Many scientific studies of wildland fire have been conducted that describe the interactions between climate, weather, and wildland fire (Chandler et al., 1983; Cheney & Sullivan, 1997; Davis, 1959; Johnson & Miyanishi, 2001; Pyne et al., 1996; Schroeder & Buck, 1970). This section presents a brief glimpse at the rich knowledge of wildland fire and its interactions with weather and climate that have been described over the past century.

2.4.1. Wildland fire

Weather and climate influence a fire's ignition, the fuels that burn, and the environment in which the fire burns. Climate is one of the principal determinants of vegetation distribution and productivity (Fig. 2.1). Vegetation in similar climates has adapted similar characteristics that influence fire. For example, in Mediterranean areas, vegetation growth occurs in the spring, and plants have developed mechanisms to conserve moisture during the long drought (Naveh, 1975). Similarly, coniferous forests have developed in the boreal regions of the world in response to the long winters with subfreezing temperatures and short summer growing seasons typical of the subarctic and cold continental climate. The boreal forest is located in the northern regions of North America in Canada and Alaska, and in Eurasia in Sweden, Norway, Finland, Russia, Kazakhstan, and Siberia. Precipitation is low but exceeds evaporation. As in the Mediterranean regions of the world, naturally occurring fire often results in the combustion and consumption of the aboveground vegetation.

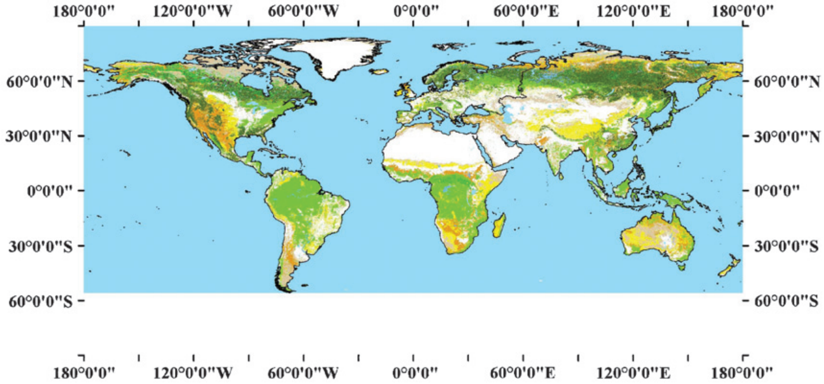

Figure 2.1. Global distribution of tree, shrub, and herbaceous vegetation, which is a result of climate. Herbaceous vegetation indicated by yellow, shrub by orange, broadleaved trees by light green, needle-leaved trees by dark green, and mixed trees by olive. Sparse vegetation is indicated by tan. (Modified from source map (European Commission Joint Research Centre, 2003)).

Globally, humans have used fire as a tool that has largely shaped the current status of the world's forests. This has been accomplished by both the introduction of fire into areas previously immune to it and the suppression of fire in large areas where fire has burned naturally on a regular basis. Humans and fire have a long history whereby prescribed fires are designed and used as a management tool to accomplish specific objectives. Wildland fires, however, are caused primarily by human carelessness and may be a destructive force to forest ecosystems (Pyne et al., 1996).

Lightning is a major cause of ignition throughout the world. In Christian et al. (2003), lightning occurrence ranged from 1 to 50 flashes $\mathrm{km}^{-1}\,\mathrm{yr}^{-1}$; however, all flashes did not result in a fire. The relative importance of lightning versus human-caused ignition varies around the world and is linked to human-population density. Lightning-caused fires often occur in mountainous areas. One of the important factors that determine the success of lightning ignition (as well as all other types of ignition) is the moisture content of the fuel where the ignition occurs (Latham & Williams, 2001).

2.4.2. Fuel moisture

Fuel moisture content is defined as the mass of water present in a fuel and is typically expressed as a fraction of the oven-dry mass of the fuel. Because of the importance of moisture in determining the ability of wildland fuels to burn, fuel moisture content is used in most fire hazard assessment and prediction systems (Fujioka et al., this volume; Roads et al., 2005) and has been correlated with area burned by wildfire in many countries (Flannigan & Harrington, 1988; for an in-depth discussion of fuel moisture and water relations in live and dead fuels, Nelson, 2001).

The cellular structure of plants contains void spaces that can contain water. In addition to playing an important role in photosynthesis and cellular metabolism, water also provides structural support to living plants. The cellular structure is maintained in the castoff foliage and branches that comprise dead wildland fuels until the dead material has decomposed. As a result, dead fuels are porous so that water is absorbed and desorbed much like a sponge; diffusion is the primary process governing the adsorption and desorption. Three weather factors strongly influence the amount of water contained within a dead fuel: temperature, relative humidity, and precipitation. A fourth factor, incident solar radiation, is important when considering the effects of ambient heating on the dead fuel (Chandler et al., 1983). Under constant temperature and relative humidity, a dead fuel particle will eventually reach an equilibrium moisture content (EMC) that is a function of the immediate environmental conditions surrounding the fuel particle. The time required for a cylindrical fuel particle to reach equilibrium with its surroundings increases as the diameter increases. EMC is seldom achieved in most wildland situations, as temperature and relative humidity are constantly changing; however, EMC is a useful concept when developing models to predict fuel moisture content (Catchpole et al., 2001; Viegas et al., 1992). Wildland fuels that are less than 0.63 cm in diameter are referred to as fine fuels and respond quickly to changes in relative humidity and temperature. Fuels of this size are often the primary carriers of wildland fire. Of the two weather variables, relative humidity is more important in determination of fuel moisture content, as it determines the moisture gradient between the air and the fuel particle. As air temperature increases, fuel moisture of dead fuels will decrease. Precipitation increases fuel moisture content; however, some dead cellulosic fuels such as grass may more readily absorb slight amounts of precipitation than similar-sized woody fuels (Weise et al., 2005a, 2005b). Reservoirs of accumulated precipitation in the form of snowpack and soil moisture also affect fuel moisture content of surface fuels (Hatton et al., 1988; McCammon, 1976).

Living plants have developed processes and mechanisms that regulate the intake of water from the soil and air and the release of water into the atmosphere. Many of these mechanisms are designed specifically to conserve water. Climatic conditions, notably relative humidity and temperature, have influenced the degree to which a plant needs to conserve water. In climates where water is deficit, plants have adapted mechanisms designed to conserve water. Among these adaptations are thick cutin (waxy coating) and hairs on leaf surfaces, sunken stomata, and the ability to store water (succulent plants). Many plants enter a form of dormancy to minimize water usage during drought periods. During this drought period, the moisture content of the plants decreases, increasing the likelihood that the vegetation will burn. Fire occurrence has been linked with drought throughout the world. In addition to the increased hazard presented by dry living vegetation, drought also causes plant mortality, increasing the amount of dead wildland fuels.

2.4.3. Types of wildland fire

Two types of combustion occur in wildland fires: flaming and smoldering (Pyne et al., 1996). Flaming combustion results when the gases released by the heating of a fuel come in contact with oxygen and ignite to produce the familiar flame of a fire. Due to the temperature of the gases and particulate matter (800–1000 °C), the gases and particles emit energy radiantly in the visible wavelengths. The flame is buoyant and forms a plume of hot gases that rise, expand, entrain ambient air, and eventually cool.

Wildland fires can be classified based on the location of the fuel that is burning. Perhaps the most common type of fire burns in live and dead vegetation that is in close proximity to the soil surface. This type of fire is known as a surface fire; oxygen is typically not a limiting factor. Some fires spread through layers of decomposing organic material and organic soils. This type of fire is called a ground fire; conduction and radiation from glowing fuel particles play a significant role in spread. Because oxygen is often limiting in this situation, smoldering combustion is often the dominant mode in these ground fires. Flames are not present. The third class of fire is called a crown fire because the fire spreads through the crowns and canopies of the shrubs or trees. In this situation, the fuels are elevated and the flame zone may or may not extend completely to the ground. Due to the depth of the fuels in shrub and tree crowns, crown fire typically has the greatest flame lengths compared to the other types of fire (also see Ottmar et al., this volume).

2.4.4. Wind and fire

Wind is arguably the most important weather and climate factor that influences the behavior of a fire (Albini, 1982; Beer, 1991; Taylor et al., 2004). There are three types of wind that are associated with wildland fire: general winds resulting from atmospheric activity, local winds resulting from unequal heating of land and sea surfaces, and winds resulting from a fire's buoyancy (also called entrainment). Most wildland fires move in one or more directions depending on the availability of fuels, wind direction, and topography. If fuels are discontinuous (e.g., as in deserts), then a fire may not spread successfully unless wind velocity and direction are sufficient to cause a fire to "leap" the gap between fuels.

Much research has been devoted to wind flow in urban and vegetated environments. A recent book compiles much of the material on the flow characteristics through these porous environments (Gayev & Hunt, 2007). Meroney (2007) discusses the effects of these porous environments on fire spread in both the urban and forested environments. These flow regimes also influence the distribution and transport of pollutants and smoke within urban and wildland–urban interface settings.

Wildland fires are often described by the direction the fire is spreading relative to the direction of the wind. A fire that spreads in the direction that the wind is blowing is called a heading fire, a fire that spreads in the direction the wind is blowing from is called a backing fire, and a fire that spreads perpendicular to the wind direction is called a flanking fire. The rates and completeness of combustion often differ as a function of fire spread, which in turn influences the production of smoke.

In addition to influencing the size of flames, wind and slope also influence the rate at which a fire will spread. It is generally agreed that the spread rate of a backing fire is relatively constant in surface fuels. Rates of spread of heading fires are several orders of magnitude greater than backing fire spread rates in litter (0.02–0.04 km h^{-1}). Under the influence of high-velocity winds or steep slopes, head fire spread rates can be 0.5 km h^{-1} for logging residue fuels, 5–15 km h^{-1} for brush fuels, and 22 km h^{-1} for grass fuels (Pyne et al., 1996). Noble (1991) reported that the highest observed spread rates in grasslands in southeastern Australia were 23 km h^{-1}. Under high wind speeds and in deep fuels, flame lengths of 20–30 m are not uncommon.

Potter (2002) developed a conceptual model of plume and fire dynamics. This model describes dynamics in three layers: surface, mixing, and stable. The interaction of a fire and its plume varies in these layers, and influential atmospheric variables may change between layers. The interaction between the energy and mass released by a fire and the fire environment results in a highly turbulent region of complex fluid flows. The presence of wind further complicates these fluid flows. Various phenomena that are collectively termed "extreme" fire behavior result from this interaction. Extreme fire behavior includes long-range transport of flying embers (spotting), crown fires (Albini & Stocks, 1986; Grishin & Gruzin, 1990), fire whirls (Graham, 1957), horizontal roll vortices (Haines & Smith, 1987), blowup fires (Potter, 2002), and mass fire (Countryman, 1964). Mass fires result when a large area experiences multiple ignitions. McArthur (1967) reported that transport of burning embers of eucalyptus bark 8–10 km is commonplace in eucalyptus forests and that there are well-documented cases of spot fires occurring 19–24 km in advance of the main fire. Transport of partially combusted forest fuels has been recently reported from a crown fire in Switzerland; however, no subsequent fire was ignited, suggesting that the firebrands were extinguished before landing (Tinner et al., 2006).

While radiation and conduction are important modes of heat transfer, convection plays a significant role in transitions in fire behavior (Finney et al., 2006; Weise et al., 2005a, 2005b;). High wind speeds are linked with severe fire behavior in many regions of the world (Bureau of Meteorology, 1984; Kutiel & Kutiel, 1991; Moravec, 1990; Thomas, 1971; van Wilgen et al., 1985; Wilson, 1962). As wildland fires grow in size and energy release, their interaction with the fire environment modifies local wind flows and other components of the local environment. Under certain conditions, the water vapor that is released in combustion will condense, form a cumulus-type cloud at the top of the fire plume, and rain. If the plume collapses, downdrafts may result that cause the fire to spread in several different directions. Recent modeling and reconstruction of significant wildfires suggest that dry air introduced from high in the atmosphere can cause erratic fire behavior (Mills, 2005; Zimet et al., 2007).

Byram (1959) presented a model of the interaction between a fire and the atmosphere based on plume theory. The derivation of this model (Nelson, 1993), which assumed a neutrally stable atmosphere and no entrainment, was extended to an unstable atmosphere with entrainment (Nelson, 2003). The model essentially looked at the balance between the ‘‘the rate of conversion of thermal energy to kinetic energy in the convection column’’ (‘‘power of the fire’’) and the ‘‘the rate of flow of kinetic energy in the atmosphere due to the wind field’’ (‘‘power of the wind’’). When the rate of energy release by the fire into the convection column above the fire dominates the atmospheric winds (power of the fire is greater than the power of the wind), the fire is called a ‘‘plume-dominated fire’’ (Ingalsbee, 2005). A plume-dominated fire can behave erratically, and the entrainment winds caused by the buoyancy of the convection column can be very strong and occur from many directions.

The energy release and fluid flows associated with wildland fire are complex. Topography further complicates the fluid flows (Viegas, 2005). Until fairly recently, scientists who studied and modeled these phenomenon had to simplify the problems so that they could be analytically or empirically solved. Today, complex computer codes in computational fluid dynamics and radiative energy transport enable many of the complex fire behavior phenomena to be modeled and compared with experimental data. Instruments such as lidar and radar can be used to describe characteristics of fire plumes, including the fluid flows within the plume (Banta et al., 1992). Crown fire spread (Albini, 1996), fire spread in the solid and gas phases (Porterie et al., 2000), fire whirls (Battaglia et al., 2000), transition from surface to crown fire (Cruz et al., 2006), transition from no-spread to spread (Zhou et al., 2005), and firebrand generation and transport (Sardoy et al., 2007) are just some of the complex problems now being studied by fire scientists throughout the world. One of the current frontiers in fire behavior modeling is modeling the coupling between a fire and the atmosphere (Coen, 2005; Linn et al., 2002).

Interaction between a fire and the local weather determines the transport of the combustion products. Wildfire smoke is buoyant because it is released from the combustion zone at a temperature that is much greater than the ambient air temperature. Because of this buoyancy, smoke in the buoyant plume will rise, disperse, and cool until it reaches a height in the atmosphere at an equivalent temperature. The presence of temperature inversions in the lower atmosphere will restrict smoke dispersion. Temperature inversions result when cooler air becomes trapped under warmer air; this phenomenon often occurs in mountainous terrain. As a result of the temperature inversion, smoke can become trapped under the inversion resulting in unhealthful conditions. A fire of sufficient size and energy release rate has the ability to "break through" an inversion layer, which results in increased venting, smoke dispersion, and fire behavior.

Nocturnal smoke transport resulting from low-intensity fires in relatively flat terrain is strongly influenced by micrometeorological conditions and topography. Smoke can flow significant distances along small drainage channels, ending up in areas such as highways, creating local visibility hazards (Achtemeier, 2005; Achtemeier & Paul, 1994). In the southern United States, clear skies and light winds are critical to the movement of smoke in this manner.

The transport of smoke from wildfires can be long range, occurring at global scales (Bertschi & Jaffe, 2005; Damoah et al., 2004). In this instance, smoke from fires becomes mixed into the lower atmosphere at heights up to 6 km. In some instances, fires have been energetic enough to inject smoke into the upper troposphere/lower stratosphere but this has generally been considered a rare occurrence (Fromm & Servranckx, 2003). The long-range transport of smoke from wildfires may have political implications, as the world becomes a global community. The large-scale deforestation and fires associated with land clearing in the tropics have been implicated in climate change (Hao & Liu, 1994; Levine, 1991), and biomass burning has been shown to impact atmospheric chemistry and dynamics (also see Goldammer et al., this volume).

2.5. Conclusion

At the global scale, climate, vegetation, and fire interact to produce a complex pattern of fire occurrence. While we have had an understanding locally of weather and fire occurrence at the scale of individual countries, we have only recently been able to view fire occurrence globally (Fig. 2.2). Satellite imagery has greatly improved our ability to look at large-scale connections between wildfire occurrence, vegetation, and climate. The planned use of fire at smaller scales may not be as readily detected by these sensors, suggesting that fire is a complex phenomenon globally. As Pyne so eloquently stated, Earth is a fire planet (Pyne et al., 1996).

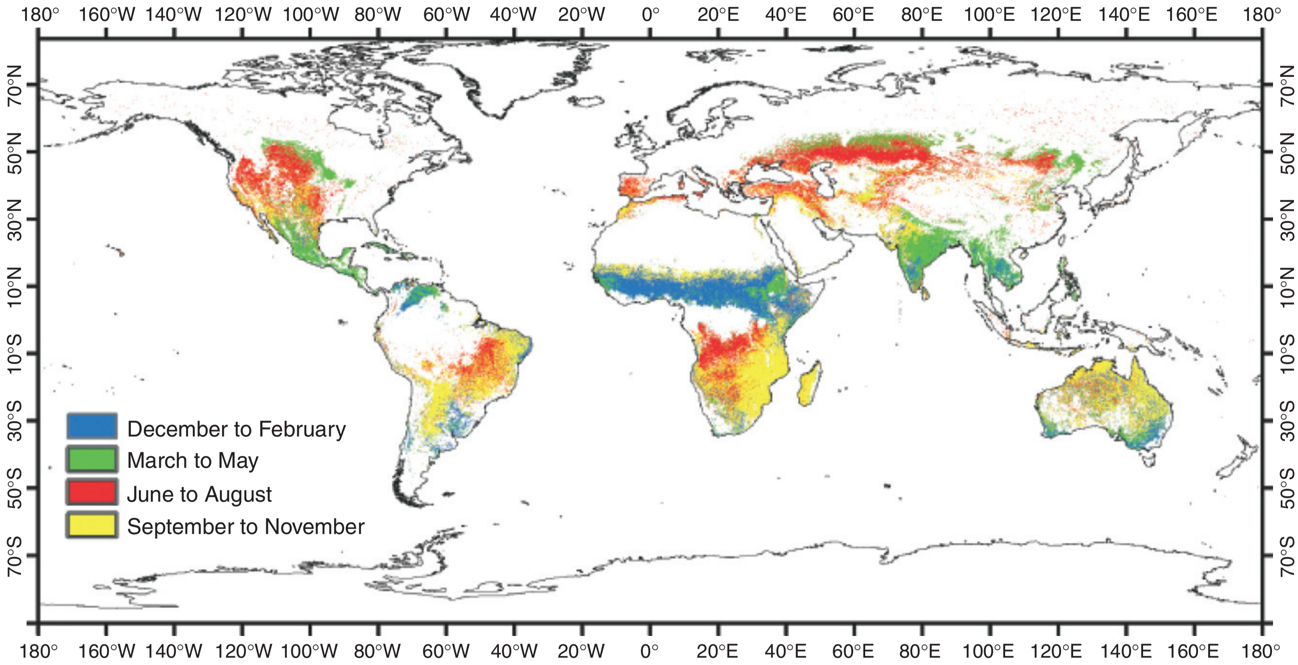

Figure 2.2. Global seasonal fire activity estimated using data from the space-based AVHRR sensor for the period 1982–1999. (From Carmona-Moreno et al., 2005.)

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