CHAPTER 11

Lightning and Forest Fires

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I. INTRODUCTION

Lightning ignition of wildland fuels plays a major role in the maintenance and evolution of ecosystems. Lightning not only ignites fire but also weakens trees, facilitating insect and disease attack, causes physical damage, and kills trees and groups of trees (Taylor, 1973). Lightning ignition may also play a large part in forest response to global climate change.

Fire can also alter lightning. Cumulus clouds, called pyrocumulus, can be formed under the proper conditions by large fires. Pyrocumulus clouds have a high proportion of positive cloud-to-ground lightning, the opposite of lightning from a "normal" cumulus (Latham, 1991). One hypothesis for the cause is an interaction between the earth's electric field and the fire (Vonnegut *et al.*,1995). Smoke from fires can apparently cause inverted storms over a large area (Lyons *et al.*, 1998a).

In this chapter, we will show how the predominant mechanism for lightning ignition works and how this knowledge can be used for forest health and fire management. We will discuss worldwide lightning and fire patterns. Before discussing ignition and other consequences, a brief introduction to lightning is supplied; it is a subject not usually discussed in a forestry curriculum.

II. LIGHTNING

A. The Origin and Characteristics of Lightning

Lightning is an energetic electrical discharge caused by the separation of positive and negative charge in clouds leading to voltage differences of order 10–100 MV. The weight of the evidence shows that the process of charge separation requires the presence of water substance in all three phases—solid, liquid, vapor (Williams, 1989). Such a condition is called mixed phase. The mixed phase region of the atmosphere is bounded below by the 0°C isotherm (where ice particles melt) and above by the −40°C isotherm (where supercooled liquid water is spontaneously transformed to ice). Under typical conditions, the mixed phase region is 4000–5000 meters thick. Though a wide variety of meteorological conditions can lead to lightning, for example, isolated air mass thunderstorms, frontal storms, and snowstorms, the presence of a mixed phase region appears to be a necessary condition for lightning generation.

Separation of positive and negative charge in regions with both ice particles and water droplets (mixed phase) is thought to be caused by the collisions of ice particles prevalent in such conditions: graupel and ice crystals (or smaller graupel). Graupel are millimeter to centimeter-sized hydrometeors, which grow by the accretion of supercooled cloud droplets. Ice crystals grow by water vapor deposition in a mixed phase environment at the expense of the liquid water because the equilibrium vapor pressure with respect to ice is less than the vapor pressure with respect to liquid. In ordinary thunderstorms, for reasons that are still poorly understood, negative charge is selectively transferred to the graupel particles and positive charge, to the smaller ice crystals. The faster falling graupel particles carry negative charge downward relative to the positive charge at higher levels, creating the positive thundercloud dipole. The resulting lower negative charge region is typically in the −5 to −20°C zone with the positive charge at higher (colder) levels. In summertime, the lower negative region is 5–7 km above mean sea level, with the positive region at 7–12 km. This positive dipole is responsible for the two most prevalent lightning types: intracloud (IC) lightning and cloud-to-ground (CG) lightning.

Intracloud lightning is a discharge bridging the upper positive and lower negative charge of the thundercloud dipole and is contained entirely within the cloud, therefore playing no role whatever in fire initiation at the ground. IC lightning is almost invariably the first lightning to occur in a developing storm; some storms produce only IC lightning. The IC rate can become very large during strong convective surges when deep mixed phase development is underway. Though some IC flashes can be quite energetic, the majority have smaller peak currents and smaller charge moments (the charge amount multiplied by the distance the charge moves) and involve less total energy than CG flashes. One important reason for the difference is that IC flashes can occur over small scales (hundreds of meters) whereas ordinary negative ground flashes are required to bridge the typical gap to ground of 5000–7000 m.

The lightning ground flash, as the active player in forest fire initiation, deserves more detailed discussion. CG lightning is most commonly initiated within the cloud, in the vicinity of the lower charge reservoir (usually negative). An ionized path, the stepped leader, is forged through the air toward ground in a region of high electric field. This stepped leader carries the large negative potential of the lower charge region toward Earth. As the stepped leader nears the Earth, an intense electric field develops between leader and ground. The field promotes electrical streamer propagation upward from elevated points on the ground that can connect to the approaching leader. When a connection is made, the bright, high-current (10–100 kA) return stroke is initiated and propagates upward toward the cloud at a speed approaching that of light ($1\text{–}2 \times 10^8 = \text{m s}^{-1}$). For reasons not well understood, this leader-return stroke sequence is often repeated at intervals of a few tens of milliseconds, causing the characteristic flicker of lightning. The extraordinary brightness of the return stroke channel may give the impression that the lightning channel is very broad. In reality, channel diameters are in the range of millimeters to centimeters, an important consideration for the modeling discussion of Section V (e.g., Orville and Helsdon, 1974).

In the majority of ground flashes, the return stroke current peaks, in less than 1 μs, to values in the range of 5–30 kA and then promptly decays in a few hundred microseconds. Despite the extraordinary peak power in such events (upwards of 10^{12} W), both observations and simulations have shown that the short duration of the return stroke is inadequate to raise trees and other flora in its path to kindling temperature and initiate fire (Taylor, 1969; Darveniza and Zhou, 1994).

In about 30% of return strokes, a sustained current of low amplitude, a continuing current, is observed to flow in the channel to ground immediately following the current peak for a period varying from milliseconds to hundreds of milliseconds (Uman, 1969). The conditions necessary for continuing currents are still not well resolved, but observations suggest that larger-than-usual reservoirs of electric charge in the cloud are necessary to sustain long continuing currents and that the return strokes initiating them are somewhat smaller in current amplitude than others. The early ground flashes in a developing storm, when the charge reservoir is still of modest size, seldom exhibit continuing currents. The largest and most energetic continuing currents are observed by ELF methods (Burke and Jones, 1996; Cummer and Inan, 1996; Huang *et al.*, 1999) beneath the extensive stratiform regions of precipitation common in mesoscale convective systems (Williams, 1998) and large winter snowstorms. Flashes having at least one stroke with a continuing current are called hybrid flashes. Strokes within flashes without a continuing current are called discrete strokes.

Approximately 90% of CG flashes worldwide transfer negative electric charge to ground. The 10% positive minority, whose physical origins are still poorly understood, are more prevalent in the dissipating stages of local thunderstorms, in the broad stratiform regions of mesoscale convective systems, in winter storms, and in thunderstorms ingesting smoke from fire (Latham, 1991; Lyons *et al.*, 1998a; Section VIII). The continuing current characteristics of positive and negative ground flashes are markedly different, and these differences are important in the context of fire initiation. The great majority of positive ground flashes are single stroke, and a continuing current follows almost all of these strokes. The majority of negative flashes are multistroke, and about half of these have accompanying continuing currents (Uman, 1969).

The development of statistics on parameters relevant to CG lightning has been facilitated by the availability of networks for ground flash detection, such as the National Lightning Detection Network currently operational in the United States (Global Atmospherics, Inc.) (Cummins *et al.*, 1998). This network can now locate the great majority of CG contact points within the contiguous United States and Canada to within a few kilometers spatially and within 1 μs accuracy in time. The polarity, return stroke peak current, and stroke multiplicity are now routinely archived for all ground flashes. Unfortunately, due to the limited low-frequency response of this equipment, and the limited range of the continuing current electric field change, no information on the continuing current component of ground flashes is presently available operationally. Most information on this component comes from local storm studies (Uman, 1969).

Recent studies with both the NLDN (Lyons *et al.*, 1998b) and ELF electromagnetic sensors (Boccippio *et al.*, 1995; Burke and Jones, 1996; Cummer and Inan, 1996; Huang *et al.*, 1999) have focused attention on positive ground flashes, which are likely the most energetic lightning flashes on the planet. Radar observations (Ligda, 1956) presented evidence for horizontal extension of lightning within the cloud for distances exceeding 100 km. It is now well recognized that this "spider" or "sheet" lightning ultimately connects to Earth in a positive ground flash with a long continuing current (Boccippio *et al.*, 1995; Mazur *et al.*, 1998). Such discharges are also capable of lone excitation of the electromagnetic Schumann resonances of the Earth-ionosphere cavity to levels exceeding all other lightning combined (Sentman, 1987; Boccippio *et al.*, 1995; Burke and Jones, 1996; Huang *et al.*, 1999). These spectacular discharges have also been clearly identified with sprites and elves, newly discovered luminous discharge phenomena in the mesosphere 60–90 km above the causal positive lightning. Both the energetic nature of positive flashes and their high probability to exhibit continuing currents have led to popular belief that this lightning type is the leading initiator of forest fire. This common view has been questioned, however, by Flannigan and Wotton (1991), who call attention to the large numbers of negative ground flashes with continuing current.

Lightning's potential to initiate fire has also been judged, incorrectly, on the basis of its visual appearance—"hot" lightning is bright white or bluish light and "cold" lightning has a dull red appearance. Quantitative analysis of the optical spectrum of lightning (Orville and Hendersen, 1986) has shown that the intrinsic spectra of all return stroke channels (the predominant source of lightning light) exhibit a very broad optical region, similar to sunlight. The light from very distant lightning (often referred to as "heat" lightning) is selectively filtered in the blue end of the spectrum by Rayleigh scattering, much like the light from the setting sun, leaving a predominance of red light. Lightning at closer range will suffer less selective loss of blue light and will appear whiter in color. As discussed in Section VI.B, the most critical parameter for lightning ignition of forest fuels is the presence and duration of the continuing current and not the temperature of the lightning plasma.

III. PREVIOUS STUDIES OF LIGHTNING-INITIATED FIRES

In this section, observations and summaries of lightning-initiated fires are discussed. The studies can be broken arbitrarily into three categories: early, Project Skyfire, and recent. The early studies were done before the characteristics of lightning were discovered and researched. Project Skyfire was designed to study the possibility of reducing fire numbers by cloud seeding. Recent studies benefit from lightning location data and organized descriptors of forest fuels.

A. Early Lightning Fire Research

Plummer (1912) observed:

> The same flash may strike and blast a number of trees, and the results may be quite as curious and erratic as the lightning itself. A tree may be scorched, it may be stripped of its leaves, it may be cleft longitudinally, or, more rarely, severed horizontally. Pieces of bark or wood may be torn off in strips. One-half of a tree's crown may be withered, the other half remaining unharmed. Sometimes the bark is stripped from only one side, occasionally without a trace of burning; at other times it may be riddled, as by worms, with a multitude of little holes. The lightning furrow on a tree is usually single; but it may be double, usually in parallel lines. Furrows may be oblique or spiral, the current in such cases following the grain of the new wood. If the tree is inflammable or is rendered very dry by the flash a fire may result. In other cases the dry duff or humus at the base of the tree is ignited by the flash.

This description is entirely adequate for today's observations.

Plummer's attempt to explain the wide range of visible effects hypothesized distinctly different "upward-going" and "downward-going" flashes to ground, causing different kinds of damage to trees. He does not specify what damage is caused by which direction. As discussed in Section II, the situation is more complex. In any case, the "direction" of flashes, and their complexity, was not firmly demonstrated until 1934 (Schonland and Collens, 1934), so there was no way for Plummer to know of the complexity or to formulate a test for the hypothesis.

Another hypothesis of the time was that some species of trees were preferentially hit by lightning. Most of the research was done in Europe and on Forest Service lands in the United States (as summarized in Plummer, 1912). Unfortunately, the data were not corrected for the relative density of tree type, so the results are questionable. In fact, Plummer's conclusions state, in part, that any kind of tree is likely to be struck by lightning and that the greatest number struck in any locality will be of the dominant species, conclusions that hold today. As we shall see, some species do have a higher probability of ignition from lightning, due mainly to their differing foliage cast.

Another interesting note from Plummer is that "Lightning is extremely rare in Alaska, and no forest fires are known to have resulted from it" in contrast to about 200 reported lightning fires per year from modern reports (Bureau of Land Management, private communication). Lightning fires are currently important enough in Alaska that it was chosen for the first trials of lightning location systems for fire management.

Subsequent lightning ignition studies were done in the northwestern area of the United States because most lightning-caused fires occur there. The area includes western Montana, northern Idaho, and parts of eastern Washington, eastern Oregon, and northwestern Wyoming. For this area, in the years 1906–1911, about 15% (864 fires) of the fires on the National Forests were started by lightning (Plummer, 1912). So, for those years, the number of person-caused fires far exceeded lightning-caused fires.

By 1924, the percentage of lightning-caused fires had apparently increased —"Lightning causes an average of 1/3 of the fires in this region . . ." (Gisborne, 1924). He also noted that ". . . only one-fourth of the lightning storms start fires . . ." and that the storms occurred in seven "waves" (no duration timescale given) during the months of July and August. From data taken by lookouts (numbers are not given), the conclusion was drawn that ". . . one-fourth of the lightning storms ordinarily start fires . . ." and that storms could be categorized on the basis of fire starts into "fire-starting" and "nondangerous" types. Gisborne suggested that fire-starting storms had a much higher CG/incloud lightning ratio than the nondangerous ones. No numbers or statistics were given to support this viewpoint.

In a later report, Gisborne (1926) stated that for the years 1907 to 1925, the average percentage of all fires started by lightning was 39% for the years 1907 to 1925, 51% in 1924, and 80% in 1925. The reason given for this increase was an increase in the number of storms during 1924 and 1925 based on lookout reports. He noted that the Weather Service storm-days numbers, determined by thunder heard at Weather Service stations, were too small by a factor of three or so, when compared to the data from 170 lookout stations. Since there were four weather stations covering approximately the same area as the 170 lookouts, this discrepancy is no surprise.

Testing the hypothesis that storms could be separated into two categories, fire-starting and nondangerous, Gisborne (1926) found, based on 2186 reports covering 3 years that stated definitely whether or not the storm was a fire starter, "safe" storms (nondangerous) had about 30% CG flashes and the "dangerous" (fire-starting) storms had about 40% CG flashes. He did state that 1046 additional reports gave CG percentages, but the storms were not classified, so those data were not used (!). Besides rejecting data, another problem with the analysis is that more than one lookout can count a given lightning flash.

Gisborne (1931) later found, based on 8128 observations made between 1924 and 1928, that safe storms had 24% CG lightning and dangerous ones had 44%; that is, storms having high percentages of in-cloud lightning caused more fires than those having low percentages. No mention is made of how many observations were made but not included in the data used. He does note that "before the degree of lightning-fire danger can be estimated satisfactorily, fire weather forecasts must consider other factors—the characteristics of the storms and probably the seasonal and current moisture content and inflammability of the forest materials" and that ". . . thunderstorm frequency alone is not a dependable criterion of the probability of lightning-caused fires." The hypothesis that thunderstorm type alone is sufficient for fire prediction is thus not proved, and lightning counts are not directly correlated to fire starts. Rainfall accompanying safe storms was observed to last 43% longer than that from dangerous storms, according to Gisborne's data. So, are safe storms safe because ignited fires are put out by rain or because there are fewer CG flashes in them? Gisborne does not answer this question.

Morris (1934), although not proposing an ignition mechanism, came to several conclusions based on an extensive study of lightning and fire reports by fire lookouts in Oregon and Washington. Important for our exposition is this subset of conclusions:

1. ". . . No more fires per acre occur in one altitude class than in another"; that is, lightning fires, at least in Oregon and Washington, do not have a bias for high altitudes;
2. ". . . It is evident that danger zoning for lightning fires, if based solely on previous [historical] distribution of the fires is likely to be very inaccurate and unreliable";
3. "No definite lightning storm lanes or frequent 'breeding' spots were found";
4. Thunderstorm days can be classified to indicate fire-starting potential (the classes were similar to those of Gisborne (1931); and
5. Storms accompanied by high rainfall led to fewer fires than storms that had less rain.

Results 1 and 3 are contrary to anecodotal evidence that lightning strikes preferentially on ridges or peaks, rather than in valleys. Result 5 supports the "obvious"; storms often put out, through rainfall, the fires they start. We will have more to say about Results 2 and 4 later. Morris did not present IC/CG ratios or percent IC in a way usable for separating storms.

Barrows *et al.* (1977) summarized lightning-caused fire data for the years 1931–1973. For the first time, lightning fire statistics are given in terms of a stated density, rather than by arbitrary classification of land areas or by Forest Service Forest. Over this period, the average number of lightning-caused fires in the Region 1 National Forests (Montana, northern and central Idaho, and northern Wyoming) was 0.85 fires per 100 km^2/y. The standard deviation was 0.41, indicating a high variability from year to year. The density also varies over the landscape. This finding reinforces the earlier ones of this section that the lightning fire density is highly variable from year to year and place to place. No lightning statistics to compare to these numbers are available because the large lookout network studies had been discontinued, and remote lightning locations were yet to come. The percent of total fires caused by lightning is 77% averaged over the years studied. This percentage has been nearly constant since 1931.

The increase in the percentage of lightning caused fires from 15 to 77% over the years between 1912 and 1931 is curious. Plausible reasons for this increase include less and more careful logging activity, a reduction in man-caused fires, better reporting of fires in remote areas, fuel complexes becoming more fire-prone to lightning ignition due to suppression, a significant reduction in fires caused by railroad activity, and/or a general change in climate. Establishing the relative contributions of these proposed explanations is a difficult task.

All the studies in this section share one major flaw. Except for a passing remark in Gisborne's (1931) study, the tacit assumption is made of a correspondence between number of CG flashes and/or the relative amount of CG and in-cloud flashes and the number of fires that result. Rainfall is assumed to influence the number of fires through immediate wetting of the fuels either before or after ignition. The fuel type is only broadly considered, that is by predominant tree species, and fuel state is not considered. (Fuel type and fuel state are loosely defined but useful terms. Fuel type includes the biological and physical descriptions appropriate to a location. Fuel state is the moisture content of the various sizes of fuels.) Classification of thunderstorms either by IC/CG ratio or by air mass or frontal, or other schemes, was perceived to be the most useful information for prediction of lightning fire incidence.

B. Project Skyfire

Project Skyfire began with the speculation that cloud seeding might be used to reduce lightning-caused fires—either by increasing rain or by influencing the thunderstorm to alter lightning production (Schaefer, 1949). As the observations and studies of 1912–1934 showed (see Section II.A), thunderstorms with low rainfall and low CG count were thought to be responsible for a majority of the fires in the northern Rocky Mountains, the northwest forests of Oregon and Washington, and the forests of northern California. After the cloud-seeding demonstrations of Project Cirrus (Schaefer, 1953), the Skyfire project was born in the Northern Rocky Forest and Range Experiment Station (Barrows, 1954). The aim of the project was to reduce lightning by either overseeding mature storms or by seeding early in the storm's development to initiate precipitation in the cloud. Early precipitation would cause cessation of rapid growth, reducing the amount of lightning. Enhancement of rainfall was not the aim of Skyfire, although earlier work (e.g., Gisborne, 1931) indicated that storms having high rainfall amount were accompanied by fewer fires than storms with low rainfall.

The investigation of cloud types and locations led to preliminary cloud seeding in 1956–1957 in Arizona and Montana (Barrows *et al.*, 1958) to test the effectiveness of ground-based and airborne silver iodide cloud-seeding generators. Fuquay and Baughman (1969) found, through research carried out in Montana, that the number of CG lightning flashes might be suppressed by cloud seeding but that a larger data sample and a properly randomized experiment were necessary for a definitive conclusion.

By 1976, the final analysis of Skyfire data on randomized seeding from the 1960's was complete (Fuquay, 1974; Baughman *et al.*, 1976). The conclusions were that cloud seeding could reduce the frequency of CG flashes by more than one-half and that the average continuing current duration might be reduced by as much as one-fourth. The possibility that reduced rainfall accompanies reduced lightning is mentioned. For lightning reduction, seeding in the early stage of cloud growth was found most effective.

A good summary of the cloud-seeding and lightning reduction experiments as well as a critique can be found in Dennis (1980), who takes issue with the analysis of Baughman *et al.* (1976). As with the majority of weather modification results, there is no broad consensus on the efficacy of cloud seeding for lightning suppression or rainfall enhancement. No conclusive proof was found that cloud seeding reduces either the number or severity of wildfires. As happens often in scientific research, however, the by-products of Skyfire proved at least as useful as the main product.

One of the important results was to further the conjecture (McEachron and Hagenguth, 1942; Berger, 1947; Malan, 1963; Loeb, 1966) that the continuing current might be the part of the lightning discharge responsible for ignitions in forest fuels. Relating the current behavior of an individual lightning flash to the incidence of fire at the same location is clearly a challenging task, and, for this reason, few observations are available. Fuquay *et al.* (1967, 1972), in two investigations, reported on 11 CG fire-starting flashes containing continuing currents varying from 40 to 280 ms in duration. They used triggered photographs of lightning as well as electric field recordings to determine the location of the flashes as well as their composition. Spotters in light aircraft searched the lightning terminus locations for fires. A ground investigation followed the aircraft observation. In addition to the fire starters, five nonstarting strikes, two hybrid and three discrete, were studied. Every fire considered was started by a flash with a continuing current longer than 40 ms. These observations led to the conclusion that earlier speculations were correct; the continuing current is the major cause of lightning-caused fires in forests.

Skyfire results also included measurements of lightning IC/CG ratios (Z values, Boccippio *et al.*, 2000) for seeded thunderstorms versus nonseeded storms. The ratios were $Z = 4.4$ for seeded storms and $Z = 3.0$ for nonseeded storms. Both of these values are higher than the Gisborne (1931) data of $Z = 2.9$ for non-fire-starting storms and $Z = 1.3$ for fire-starting storms. The Skyfire data were taken with electronic recording equipment and cameras rather than by lookouts, which might explain the difference. Boccippio *et al.* (2000) found values $Z = 3$ to $Z = 7$ for the same geographic locations. Evidently there is a high variability in the IC/CG ratio; separation of storm fire-starting effectiveness based on this ratio needs further study.

Skyfire came to a close in the early 1970s, having established that the cause of lightning fire ignitions was the continuing current in the lightning flash. Evidence was gathered that cloud seeding, if done properly, could reduce the number of CG discharges and the incidence and duration of continuing current discharges from a given storm. The research leading to the models discussed later in this chapter had its origins in Skyfire.

C. Recent Studies

Recent studies of lightning-caused fires benefit from two major data sources not available to earlier researchers: organized fuel state descriptions and accurate regional CG lightning location. Fuel type and fuel state, principally moisture content in specified fuel arrays, have been combined into fire danger indices for forest managers. Generally, fuels in a given fuel type are distributed in the forest by amount of dead biomass stratified by size. Each size adsorbs water from rain and moist air. The amount of water in each size class is combined into an index indicating roughly the severity of a fire should one start. The United States uses the National Fire Danger Rating System (Deeming *et al.*, 1977), and Canada uses the Canadian Fire Weather Index System (Van Wagner, 1987). Although these systems are not identical, they are similar in that each has indices that, for various fuel types, indicate fuel moisture. The indices are routinely calculated and archived, presenting a uniform database to use with lightning locations.

Lightning location is accomplished by detecting low-frequency electromagnetic radiation emitted by lightning (Section II). Either triangulation or time-of-arrival techniques can be applied. CG (positive and negative) and IC strokes are distinguished by differences in the radiation patterns. Systems have been in use since about 1978, first in Alaska and subsequently in the United States and Canada. Early systems claimed accuracy of location in the range 1–10 km. Recent systems, using Global Positioning Systems (GPS) claim accuracy on the order of 500 m (Cummins *et al.*, 1998). Efficiency of 95% detected CG events or better is claimed for modern systems. Position accuracy and efficiency depend on the location of the CG with respect to the receiving stations in the detection network. CG locations are archived by the company that now operates the networks: Global Atmospherics, Inc., of Tucson, AZ. Several recent studies use fuel indices and lightning location together with fire reports and weather reports and are summarized later. Flannigan and Wotton (1991) studied the relationship between fires and lightning in northwestern Ontario, Canada. They found, essentially, that negative lightning ignited more fires than positive lightning and that the duff moisture code and the multiplicity of the strokes in the lightning flash, for negative strokes, were important independent variables. Although not specified in their work, it seems that stroke multiplicity has a connection because the probability of a continuing current in a flash is weakly connected to the number of strokes (Uman, 1969).

McRae (1992) found no connection between elevation, slope, aspect, or topographic unit and lightning fires for the Australian Capital Territory, supporting the much earlier findings of Morris (1934). But Van Wagtendonk (1991) did find altitude dependence for lightning-ignited fires in Yosemite National Park and justified this dependence on the grounds of vegetation type and preferred lightning storm development. Renkin and Despain (1992) found no altitude dependence for lightning fires in Yellowstone Park but did find a preponderance of lightning fires in mature stands of Douglas fir, spruce fir, and decadent lodgepole, as opposed to successional lodgepole and multiaged lodgepole stands. In addition, a threshold level of moisture in fine fuels, 13% of dry weight, was found above which fires would not continue to burn after an ignition.

Meisner (1993) studied lightning-caused fires for the period 1985 to 1991 in a small area in Southern Idaho. The lightning strikes were randomly distributed over the terrain, as were the fuel classes. The procedure used by Meisner was to break down the area by species and then calculate the efficiency on a per-species basis. Lightning-caused fire efficiencies were calculated for each 100 km^2 pixel on the map and then averaged for the fuel classes in the sampled area. The highest lightning efficiency was for logging slash, at 0.1 fires/CG flash, and the lowest was 0.003 fires/CG flash for agricultural crops. Efficiencies for mixed firs and Ponderosa pine were 0.02 fires/CG flash and 0.04 fires/CG flash, respectively. One of the findings of the study was that ". . . on days when there were 100 or more detected lightning strikes, the correlations between fire danger indices and number of fires were typically doubled." This compares nicely with Gisborne's (1931) findings summarized in Section III.A; there seem to be storm day types that correspond to high fire incidence. But according to Gisborne's observations, high CG lightning amounts result in fewer fires, the opposite conclusion. Current lightning detection systems do not presently report in-cloud flashes, so no division of storms or storm days could be made on this basis to test Gisborne's (1931) statement.

Nash and Johnson (1996) thoroughly analyzed the coupling of synoptic weather conditions with local scale weather and fuel conditions, the latter expressed in terms of the Canadian fire indices, and resulting fires in Canadian boreal and subalpine fuel types. They found, analyzing 2551 fires and 1,537,624 CG lightning flashes, that the best fuel state predictor for lightning fires was the Fine Fuel Moisture Code index. Above the moisture index of 87 (equivalent to a moisture content of 14% of dry weight; higher index value means lower moisture), very close to the 13% value found by Renkin and Despain (1992) for fires in Yellowstone National Park, the lightning-caused fire efficiency (number of fires/number of CG's in the same area) increased rapidly. The highest efficiency found was 0.06 fires/CG flash. No overall average was given, but typical values were between 0.01 and 0.04 fires/CG flash, in the same range as the Meisner (1993) values. Nash and Johnson also found that lightning efficiency of fires was higher under synoptic high pressure, when persistent rainfall was not expected. This description presents yet another "storm day type" stratification.

Rorig and Ferguson (1999) generated a discrimination rule for selecting "dry" vs. "wet" thunderstorm day occurrence in the Pacific Northwest. The rule uses the dewpoint depression at 85 kPa and the temperature difference between 85 and 50 kPa. No connection was made to fires.

For this chapter, we gathered fire and lightning locations, as well as fuel types as data for constructing map layers in a Geographic Information System (GIS). The data cover western Montana, northwestern Wyoming, and northern Idaho, as is apparent from the state outlines on Figures 1, 2, and 3 (see color insert). Summaries of lightning flash position data were obtained from the Bureau of Land Management (BLM) and Global Atmospherics, Inc., and fire data from the USDA Forest Service and Department of Interior land management agencies (primarily the BLM). Figures 1, 2, and 3 show derived spatial layers for fires, lightning density, lightning ignition efficiency, and fuel type for the years 1986–1992. In each of these figures, the fire locations are plotted as black dots. All the pixels shown on these maps are 10 km on each side (Lambert projection); the data were aggregated upward from 1-km pixels.

From Figure 1, it is evident that lightning density and fires are only loosely connected. That is, lightning is a necessary (by definition), but not a sufficient condition for ignition. Other factors, such as fuel type and moisture, must be considered. Notice that, in the very small areas of high strike density, no fires occurred over the time period covered by the maps. By inspection, roughly half

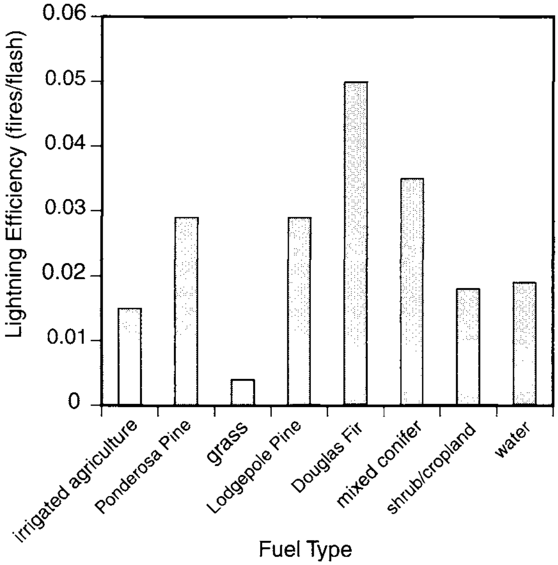

FIGURE 4 Ignition efficiency as a function of fuel type.

the fires occurred in the minimum lightning density category of 15–199 strikes/100 km^2. The results shown in Figure 4 indicate that the average ignition efficiency over the 7-yr period is about 0.026 fires/CG flash, combining positive and negative flashes. Because of the importance of fuel type and state, lightning density maps cannot provide a surrogate for fire density maps, either for past fires or for future fires, unless carefully combined with other data. This finding echoes Gisborne's results of 1931. Unfortunately, Gisborne did not calculate an efficiency that can be compared with the recent studies. We have not tested the separation of storms or storm-days into safe or dangerous categories. Fuel type and fuel state are of more importance than the incidence of lightning in determining fires (Figure 3). World fire and lightning maps (Figures 18 and 19; see color insert) support this view. The 7-yr data span covers a wide range of fuel states and can be considered as integrating over them. Lightning efficiency values were extracted from the map data on a 1-km pixel size. Figure 4 presents the lightning efficiency as a function of fuel type. The highest lightning ignition efficiencies are in the Douglas fir and spruce fir/mixed conifer fuels. Meisner's (1993) data did not have a Douglas fir fuel type, so no direct comparison for that fuel type can be made. His value for Ponderosa pine was 0.042 fires/CG flash as compared to 0.029 fires/CG flash for this analysis. This discrepancy is due at least in part to a smaller area and smaller time period in the Meisner study; the analysis done for this chapter spans a much larger area and time period.

Nash and Johnson (1996) found ignition efficiency values ranging from 0.01 to 0.04 fires/CG flash, in the range of our analysis.

The lightning-caused fire ignition efficiency for water (Figure 4) is 0.019 fires/CG flash. This is a good example of the misleading effect of small sample size, as pointed out in Nash and Johnson (1996). The water area in our maps is 26,247 km^2 as compared to a wooded area of 690,596 km^2 and grass, shrub, and cropland area of 6,072,307 km^2. The water area is almost all in two large lakes with wooded surroundings. Reports of fire locations are often not accurate, and a small position error can place a fire on the water instead of on the shore. All these factors lead to an error that appears large because of its absurdity and comparative magnitude but that is actually very small.

More work is needed in the realm of lightning-caused fire efficiency. From the studies summarized here, the efficiency apparently depends on a multitude of factors. Among them, in order of spatial scale, are synoptic weather conditions, fuel types, thunderstorm characteristics such as rainfall and lightning rates, lightning characteristics such as positive, negative, and hybrid, and fuel state, predominately moisture content of fine fuels. Broad agreement is evident among the studies that the efficiency values for fuels and fuel conditions of interest are roughly between 0.01 and 0.05 fires/CG lightning flash. The next sections will explore the details of the interaction of lightning with fuels and the physics of the ignition process to explain the low efficiencies.

IV. INTERACTION BETWEEN LIGHTNING AND FUELS

A. Lightning Paths on Trees

The concept of "upward" and "downward" discharge directions (Plummer, 1912; Section III.A) was generated by observations of termination of the discharge path at some specific point on the trunk of the tree. This is caused by flashover, a phenomenon that occurs on towers, electric poles and other elevated structures including trees (Darveniza, 1980). That is, at some position on the tree or other conductor, the discharge "decides" to go to ground through the air rather than continue along the conductor. The details of this phenomenon are not well understood, especially with respect to trees. But the fact that it is not universal, that sometimes the discharge does proceed all the way down the tree (or conductor), even out the root structure, could have been the source of Plummer's (1912) hypothesis of up-going and down-going strikes. The actual physics of the lightning-tree-ground interaction during a lightning discharge has not been thoroughly explained.

Plummer (1912) proposed that an increase of tree conductivity due to wetting by rain had a part in ignition. The lightning strike path usually follows the cambium layer of the tree because it has higher conductivity than either wet bark or the woody interior of the tree (Defandorf, 1955). Cambium cells transport the water necessary for the tree's operation and exhibit higher conductivity parallel to the direction of growth of the tree as opposed to perpendicular to that direction (Du Moncel, 1877). Lightning scars on trees almost invariably feature blown-off strips of bark, leaving a mark on the trunk showing that the path was under the bark. Also, the path of the strike is very often spiral, following the spiral long axis of the cambium cells. Sometimes, of course, the lightning path is straight down the tree and/or on the bark surface (Taylor, 1973).

B. Ecological Damage Not Involving Fire

Many lightning strikes to trees do not result in fire. In fact, a strike to a tree often causes only mechanical damage, up to and including complete destruction of the tree (Plummer, 1912; Taylor, 1969). This damage could be caused by the rapid gas expansion in a return stroke, by the sudden creation of steam by a return stroke in damp rotten heartwood from a continuing current, or by both. Only the aftermath is available to show the effect, and a mechanism has not been truly identified. No statistics are available for the proportion of strikes to trees that cause damage or kill the tree without starting a fire. Because it is weakened by the strike, a lightning-struck tree can also act as a vector for insect and disease infestation, leading to insect destruction of the struck tree and infestation of trees surrounding it (McMullen and Atkins, 1962; Schmitz and Taylor, 1969). Also, there are instances, especially in the southern United States, of group-kills of trees caused by root destruction from the ground path of a discharge to one tree. Taylor (1969) provides an excellent summary of lightning effects on the forest that do not involve fire.

C. Fuels on the Forest Floor

Anecdotal evidence implies that lightning ignition of forest fuels takes place almost exclusively in the fine fuels on the forest floor. Typically, in the forests of the northwestern United States and other forested areas of the world, lightning strikes a tree and, although the connection process for lightning to ground is complex, the result is the establishment of a path down the trunk toward the ground (Figure 5). Sometimes, the strike will flash over to ground, at a height of a meter or two. The reason for this behavior is not known. The breakdown path to mineral soil, which can be considered "ground," passes, in either case,

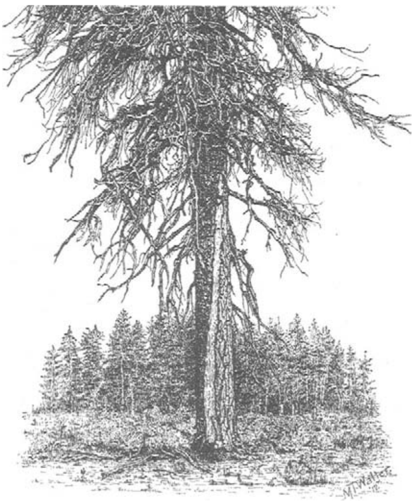

FIGURE 5 Lightning path on a tree (Plummer, 1912).

through the fine fuels on the forest floor. Ignitions occur along this path in the litter and duff layers on the forest floor (Fuquay *et al.*, 1967, 1972; Taylor, 1969). The composition of litter and duff layers varies considerably from place to place in forested and grassland areas, depending on the local ecosystem. For example, Ponderosa pine has, as do most pines, a needle very long in comparison to its diameter. Because of this, the litter layer in ecosystems in which this species is dominant is relatively thick compared to the duff layer. Firs, on the other hand, have needles that are much shorter, making for a compact duff layer and a very thin, almost nonexistent, litter layer.

Occasionally, the stroke will pass through the moist heartwood of a dead tree (snag) or a live tree. When that happens, the tree may be blown apart (Figure 6), with or without accompanying fire. Fires often burn from the inside of snags that are not blown apart to the forest floor fuels, causing holdover fires (fires that smolder for long times before they are discovered; Frandsen, 1987).

V. HOW IGNITION OCCURS

A. Formulation of the Problem

One of the most important of the Skyfire findings was identification of the continuing current as the primary cause of lightning ignitions of forest fuels

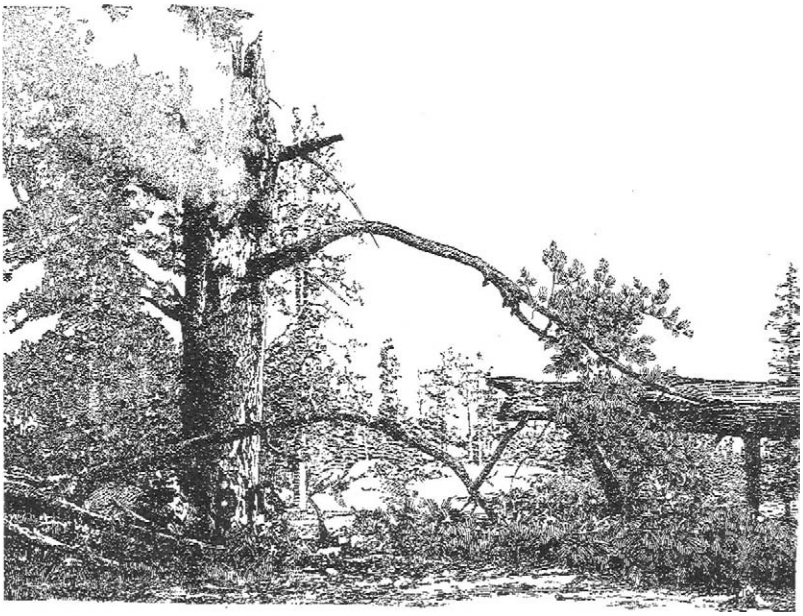

FIGURE 6 A tree demolished by lightning (Plummer, 1912).

(Section III.B). The field studies of Taylor (1969) verified that burning debris blown off trees from discrete strokes onto litter or duff fuels does not cause ignition, and Fuquay (1974) formed the conjecture that the duration of the continuing current might be important in the ignition efficiency. This information formed the basis for a model to predict fire density (fires/100 km^2) given the presence of lightning and the type and state of the fuel. That is, real-time and predicted data from reliable, convenient, and inexpensive sources, such as weather nowcasts and forecasts, and lightning location networks, would be used with algorithms to predict the incidence of fires on the landscape.

The task, then, was to form a construct or set of questions for the model. The questions are:

- What is the thermal and radiating structure of the continuing current?
- What is the energy required to ignite fine fuels?
- Is radiation or convection the predominant mode of energy transmission from the continuing current channel to the fuel?
- What experiments are necessary to establish usable parameters?
- If a predictive model is found, what is the set of data needed to implement the model for practical use?

- How should predictions be integrated with existing fire systems such as the National Fire Danger Rating System?

B. Energy Transfer from the Lightning Channel

The basic framework for ignition modeling is shown in Figure 7. A cylindrical conducting channel of hot gas, whose characteristics such as diameter and temperature are determined by a suitable physical model (Section V.C), passes into a layer of uniform fuel overlaying an electrically conductive soil layer that is the electrical ground terminal for the current in the channel. General assumptions for this framework are (1) temperature profile consistent with a hot gas arc channel model, (2) vertical penetration of the fuel, (3) infinite channel height (or at least very much longer than the depth of the fuel), and (4) no effects from horizontal current flow in the soil. Once the channel structure, particularly temperature, is established, energy transfer to the fuel depending on the mode of transfer will be calculated, with surface element A the location of maximum radiation transfer from the arc column and surface element B the location of maximum convective transfer (Figure 7). Conductive heat transfer, by diffusion within a medium, does not apply to heat transfer from the hot gas channel to the fuel (Incropera and DeWitt, 1996). Conduction does play a role in the structure of the arc channel.

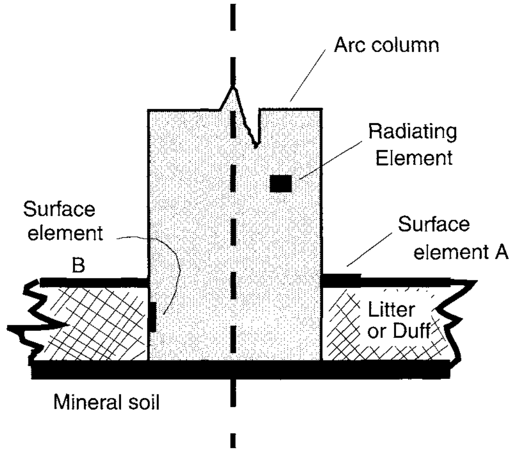

FIGURE 7 Schematic of a continuing current path through forest floor fuel.

C. Structure of the Continuing Current Channel

Details of the thermal and radiation structure of the continuing current channel were calculated using hot gas models of an electric arc channel. That is, energy balance and conservation of mass equations, together with Ohm's Law, are solved with appropriate boundary conditions. These equations were solved numerically by Uman and Voshall (1968) for a channel with no current flow such as a return stroke decay channel and by Latham (1986) with electric current flow. The latter model included radiation cooling and full physical hot gas characteristics under cylindrical symmetry. Few measurements are available for long arcs. Electrode effects dominated most measured arc characteristics (Strom, 1946; King, 1961). As a consequence, channel characteristics are poorly defined for validating models of arcs in regions away from electrodes, the relevant situation with lightning continuing currents.

Latham's (1986) model will be used to give the details of the modeled continuing current channel. The assumptions are relatively simple and have been justified (Uman and Voshall, 1968; Latham, 1986):

- Radial symmetry, giving a cylindrical arc;
- Unit length of channel, hence no axial dependence; and
- Optically thin gas, that is all radiation from the hot gas escapes the channel and is not captured and electron and ion temperatures are the same.

Values for hot gas physical constants as a function of temperature were available from numerous research studies (see Latham, 1986, for the extensive list). Using the assumptions given here, the energy conservation equation for an element of the gas in cylindrical coordinates is

$$\rho c_p(\partial T/\partial t) + \rho c_p u(\partial T/\partial r) = 1/r\{[\partial/\partial r][rk(\partial T/\partial r)]\} + \sigma E^2 - S \qquad (1)$$

The conservation of mass requires

$$(\partial \rho/\partial t) + (1/r)[(\partial/\partial r)r\rho u] = 0 \qquad (2)$$

Ohm's Law stated for the gas column is

$$j = \sigma E \qquad (3)$$

The equation of state for the hot gas is

$$p = \rho RTZ \qquad (4)$$

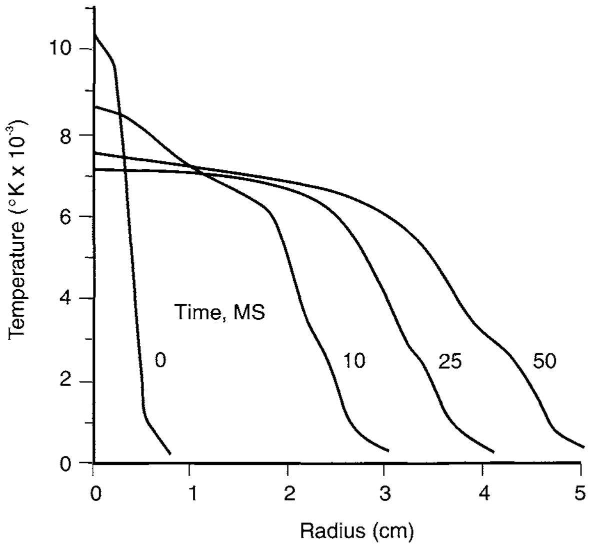

FIGURE 8 Temperature profiles of the theoretical channel as time progresses.

Boundary conditions are stated at $r = 0$ and at $r = \infty$ as

$$r = 0, \qquad \partial T/\partial r = 0; \qquad r = \infty, \qquad T = T_{\text{ambient}} \tag{5}$$

where ρ is gas density, u is radial velocity, r is channel radius, T is gas temperature, k is thermal conductivity, Cp is specific heat at constant pressure, Z is compressibility, p is pressure, R is gas constant, σ is electrical conductivity, E is electric field, j is current density, S is radiation density, and t is time.

The initial conditions are given as a radially small (0.5 cm) high-temperature (12000 K) pulse at $t = 0$ (Figure 8), simulating the return stroke channel.

Combining Eqs. (1)–(4) describing the channel behavior results in a highly nonlinear system. Various mathematical attacks to solve the equations in closed form were not successful. As a result, finite difference computer computation was applied. As usual, when a finite difference approximation is used, some conditions on the problem cannot be actualized. In the problem at hand, we cannot integrate the equations to infinite radius. Initially, the radial boundary was placed at 100 cm for a one cm channel, leading to extensive calculation times. A boundary condition, derived from the equations, circumvented this problem (Latham, 1986), allowing more rapid calculation. With the boundary conditions properly handled, temperature profiles at successive times from 0 to 50 ms for an unbounded channel result (Figures 8 and 9). The results can be summarized qualitatively as follows: energy balance in the interior of the channel is dominated by the thermal conductivity of the hot air in the channel. On the

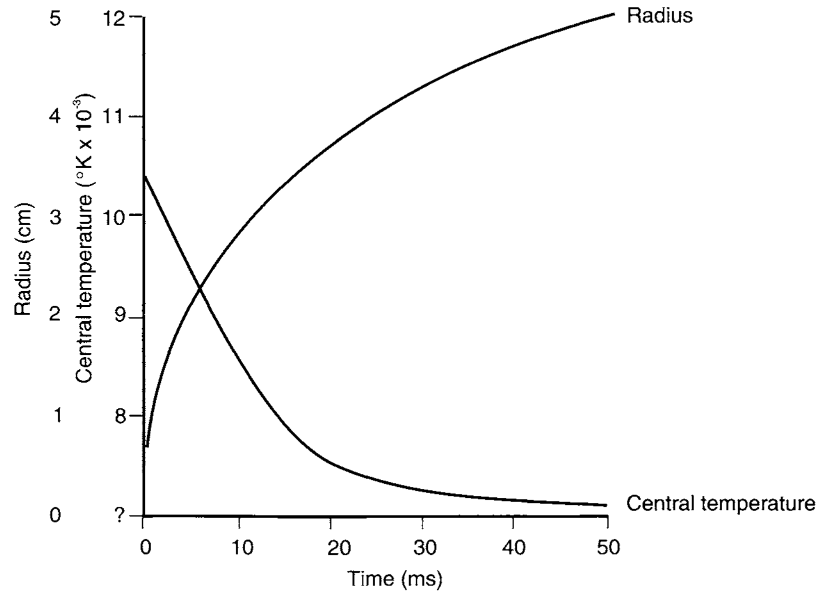

FIGURE 9 Channel central temperature as a function of time.

other hand, the radial growth rate of the channel is determined by the conductivity contrast between the ambient air and the hot channel because the edge of the channel moves outward by conductive heating at the channel edge. Basically, the radial structure at the channel edge is independent of the interior temperature (Figure 8). Also, if the current ceases, the channel temperature will decay, but the radius will continue to expand, as in the model of Uman and Voshall (1968).

Grieg *et al.* (1985), through observations coupled with calculations, maintained that turbulent convective mixing causes much faster (a factor of 2000) channel collapse than conduction. The expansion and collapse of that arc may resemble the collapse of the much higher energy return stroke channel. High-speed images of the arcs used in the experiments referred to in Section VI show no turbulent breakdown, but the energy densities are lower. Evidently, more exploration is necessary concerning the transition from stroke channel to continuing current channel.

Measurements have been made in other studies that support the model, at least in the prediction of the temperature of the arc. Latham (1984) presented an analysis showing that the ratio of the N_2^+ first negative radiation, an excited state of the nitrogen molecule, and the cyanogen (CN) radiation over the range 6000–9000 K can be used to estimate the channel temperature (Figures 10 and 11). Salanave (1965) and Connor (1967) reported strong radiation at these wavelengths, although the two wavelengths were not differentiated. An example

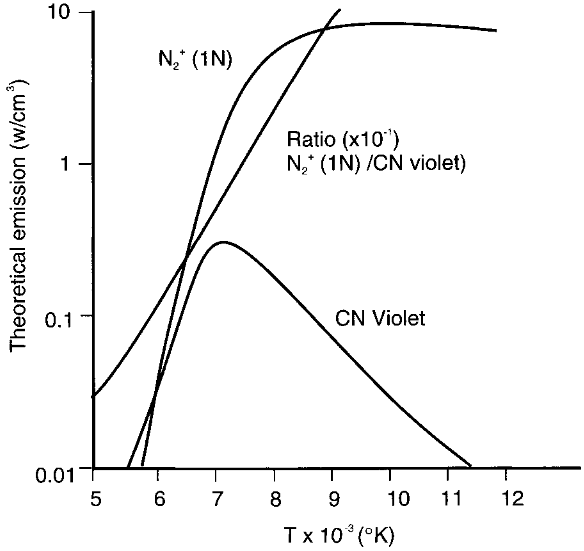

FIGURE 10 N_2^+(1N) and CN violet radiation as a function of temperature.

of the ratio measurement is given in Latham (1984); the ratio gives a temperature of about 6500 K that corresponds to the model (Figure 12). The author has made no further measurements, but validation of the model should be conducted with further spectral measurements during the continuing current phase of CG flashes.

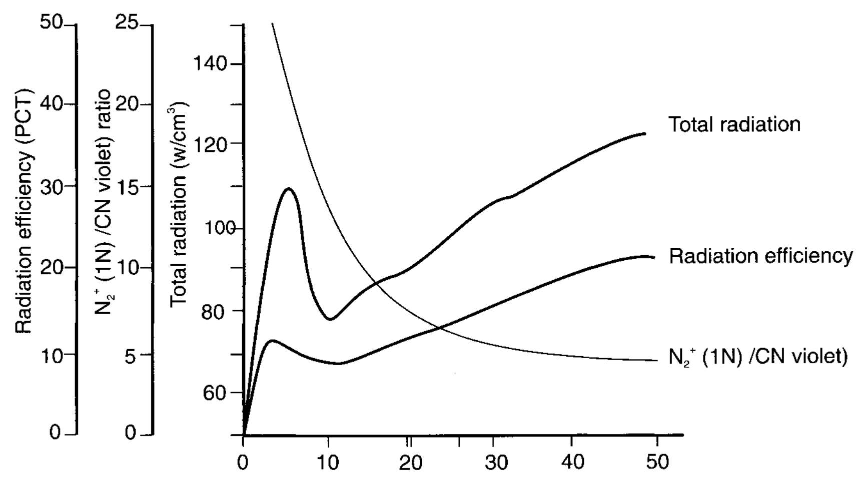

FIGURE 11 Radiation and radiation efficiency as functions of time for the calculated channel.

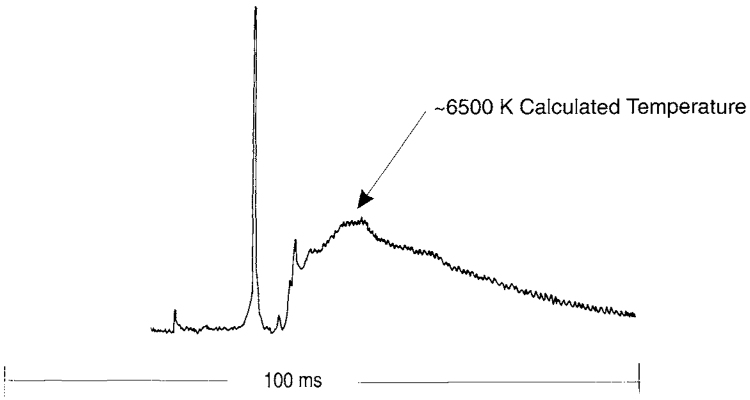

FIGURE 12 A measured $N_2^+(1N)/CN$ intensity ratio for a lightning stroke with continuing current.

D. Requirements for Fuel Ignition by Lightning

As stated earlier, forest floor fuels that are most susceptible to lightning ignition fall into three rough categories: loose, unconsolidated fuels with low bulk densities (for example Ponderosa pine or lodgepole pine litter); tightly packed small fuel particles (such as Douglas fir); or consolidated rotted fuels (such as peat). That peat can be ignited by lightning at all might be surprising at first, considering its water content and density. Not only do these ignitions occur, for example in the Florida Everglades, but the resulting fires can also smolder for long periods of time. This behavior should be explained in our model structure.

Burning (combustion) actually takes place as diffusion flames in the complex hydrocarbon gases that are "cooked" out of the fuel by heating, a process called pyrolysis. Pyrolysis is generally dependent on the temperature of the fuels (e.g., Susott, 1984). Energy transferred to the fuel by heat processes must raise the temperature to a level sufficient to initiate pyrolysis. Calculation of this temperature requires the construction of an appropriate heat (conservation of energy) equation for the heated object. These equations are usually very complex, and almost always nonlinear, because of the geometry involved and because radiation effects are proportional to T^4 (Cox, 1995; Incropera and DeWitt, 1996).

Several researchers have proposed ignition criteria for forest fuels (Martin and Broido, 1963; Simms and Law, 1967; Susott, 1984; Jones *et al.*, 1990). In general, the criteria are given in two ways: in terms of the temperature of particles at the time flaming begins and in terms of the energy flux and duration necessary to generate flaming in the material. Two ignition conditions are possible—spontaneous and piloted. In spontaneous ignition, a heat pulse is applied to the material and either ignition occurs or not. In piloted ignition, the material is subjected to either a steadily increasing or constant heat source for durations longer than a few seconds, preheating the material, and then subjected to a pulse or increase in heat. Again, ignition either occurs or not. Ignition by lightning is an example of spontaneous ignition, whereas a propagating fire is an example of piloted ignition (Cox, 1995).

In our analysis, we will rely on measured ignition criteria for short radiation pulses as a minimum of about 1.67×10^5 W m^{-2} for a 500 ms pulse (Martin and Broido, 1963), supported by measurements made by Simms and Law (1967). These ignition criteria ignore problems having to do with moisture content, physical arrangement, and the like (which act to increase the needed ignition flux) and allow us to explore the possibilities for various modes of heat transfer. The cylindrical model of Section V.C can be used to calculate theoretical heat fluxes associated with radiation and convection.

E. Theoretical Heat Flux Calculations

Referring to Figures 7 and 13, the radiation flux at patch A can be calculated. Establish a cylindrical coordinate system with its origin in the plane containing A, with the z-axis vertical and coinciding with the axis of a cylinder of hot gas with temperature T (K) and radius a (cm). Assuming a "top hat" profile for

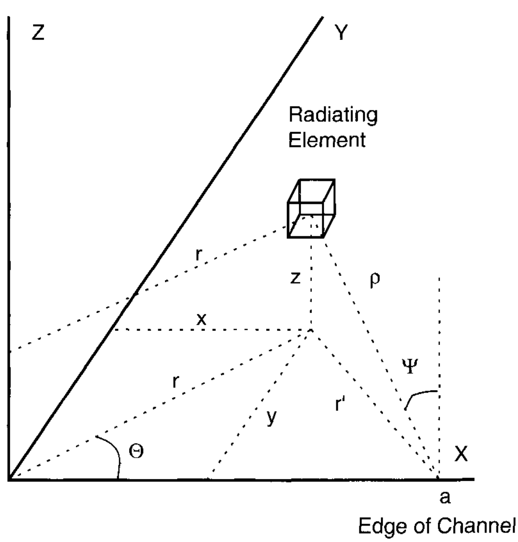

FIGURE 13 Coordinate layout for radiation and convection calculations.

the channel, if S (W m^{-3}) is the total emission per unit volume from the hot gas at constant temperature and is zero outside the cylinder, the flux at A is

$$F_A = \int_0^a \int_0^{2\pi} \int_0^\infty \frac{Sr \cos \psi \, dr d\vartheta dz}{4\pi r^2} \tag{6}$$

the variables in the problem being shown in Figure 13. With that geometry, the equation can be restated as

$$F_A = \frac{S}{4\pi} \int_0^a \int_0^{2\pi} \int_0^\infty \frac{rz \, dr d\vartheta dz}{(r^2 + a^2 + z^2 - 2ar \cos \vartheta)^{3/2}} \tag{7}$$

Integrating over z and invoking symmetry on ϑ leaves

$$F_A = \frac{S}{2\pi} \int_0^a \int_0^\pi \frac{r \, dr d\vartheta}{(r^2 + a^2 - 2ar \cos \vartheta)^{3/2}} \tag{8}$$

This integral has a singularity at $r = a$. Moving A just a little way radially from $r = a$ to avoid the singularity gives a value for the integral of $F_A = 0.3aS$ W m^{-2}.

Proceeding in the same way for a patch at B placed at $z = 0$ gives a flux of

$$F_B = \frac{S}{4\pi} \int_0^a \int_0^{2\pi} \int_0^\infty \frac{r(a - \cos \vartheta) dr d\vartheta dz}{(r^2 + a^2 + z^2 - 2ar \cos \vartheta)^{3/2}} \tag{9}$$

which reduces to $F_B = 0.5aS$ W m^{-2}.

For the present purpose, then, we take the flux from the column to be about $Sa/2$ W m^{-2} and assume some values for a growing channel. At a generously high gas temperature of 8000 K (Figure 9), the radiation heating at a radius of 1 cm is about 1×10^5 W m^{-2}, or 5×10^4 J m^{-2} for a 500-ms pulse. This value is less than the very generous required minimum energy for ignition of 8×10^4 J m^{-2} for a 500-ms pulse as established in Section V.D. Thus, although radiation heating is definitely present, it is unlikely to be a dominant part of the ignition of forest floor fuels by lightning. The relative weakness of radiation as an ignition source was also seen in the scenario developed for ignition of forest fuels by meteor fragments in Melosh *et al.* (1990).

Convective heating may be estimated for small-diameter fuels, such as pine needles, that are bathed in the gas flow of the arc. Suppose the gas temperature is 8000 K as in the previous example (Latham, 1986). The gas density is 0.0235 = kg m^{-3}, the viscosity about 1.5×10^{-3} poise (Adams, 1966). The kinematic viscosity is thus 6.4×10^{-4} m^2 s^{-1}. The diameter, d, of a pine needle from a long-needled species, such as Ponderosa pine, is about 1 mm. The velocity of the gases in an arc discharge such as a continuing current is about 2000 m s^{-1} perpendicular to the cross section of the arc (Strachan and Barrault, 1975). The Reynolds number of the gas flow is thus about 30, and the Nusselt number, Nu, is about 3 (Incropera and DeWitt, 1996). The thermal conductivity, k, of hot air at 8000 K is 2.44 W K^{-1} m^{-1} (Adams, 1966), and the heat transferred to the fuel element is about $(T_g - T_a)$*Nu*k/d or 5.5×10^7 W m^{-2}, where T_g is the gas temperature and T_a is the ambient temperature. The resultant energy deposited in 500 ms would be 2.5 J m^{-2}. The convective heat transfer is roughly three orders of magnitude larger than the radiation heating calculated earlier.

If a more solid fuel is involved, such as a duff layer, consider the wall of the fuel to be the wall of a pipe with a hot gas in turbulent flow in the pipe. Calculation for heat transfer to the wall of a pipe using the same values as for small fuel heating gives a flux at the fuel surface of about 1×10^5 J m^{-2}, again larger than the heat flux from radiation as calculated above. Under the reasonable assumptions made, the importance of the duration of the current rather than its amplitude is clear.

The scenario for ignition of forest floor fuels can, then, be summarized as follows. A return stroke, or perhaps a junction process arc establishes a path through the fuel. The high-current (tens of kiloamperes) initiating arc is followed in some cases by a smaller continuing current on the order of 100 A, lasting tens to hundreds of milliseconds. The continuing current arc, which cannot shrink, expands continuously into the fuel. The center portion of the arc, under any scenario, is hot enough to ablate completely the material in its interior, and only gas is left behind. As the continuing current stops, the central temperature in the channel decays, and the channel continues to expand. The ring of unablated material at the channel edge either has received enough energy through combined radiation and convection to maintain the ignition or not.

These approximate calculations serve to show the complexity of heat transfer from lightning continuing currents to forest floor fuels. They also lead to the conclusion that theoretical solutions of the ignition problem cannot give results sufficiently accurate for routine operations. Darveniza and Zhou (1994), having done some impulse and arc heating studies using high-voltage arcs, suggested, "It was found that the power and energy transferred to the fuels from per centimeter of the arc were much greater than those of the arc itself [sic] and were current and fuel properties dependent." This statement appears to support our view that convection transfer is more important than radiation transfer. We had already turned to experiment in 1988 to lay the foundation for a useful product, as is described in the next section.

VI. IGNITION EXPERIMENTS WITH REAL FOREST FUELS

A. Apparatus and Experimental Design

As we have shown, the interaction between the hot gas channel of the lightning continuing current and the fuels through which it passes is extremely complex. Consequently, a series of experiments was carried out to form a model that would allow calculation of ignition probabilities from easily obtained data.

An arc generator was constructed to simulate, as closely as possible, the discharge of a lightning continuing current. The arc generator used 42 12-V truck batteries connected in series, controlled by a silicon-controlled rectifier switch and initiated by either an exploding tungsten wire or by drawing the arc with a rapidly moving carbon electrode (Latham, 1987, 1989).

In all, eight types of fuel samples (Table 1), taken from the wild and representative of most forest floor types, were subjected to a range of arcs. A series resistance in the arc circuit controlled the current, and a computer-controlled silicon-controlled rectifier switch controlled arc duration. The moisture content of the fuels was varied between 5 and 40% of dry weight. In all, 1600 trials were conducted with a current range of 20–500 A and durations from 10 to

TABLE 1 Coefficients of the Probability Equation for Fuel Types Used in the Ignition Experiments

Fuel type	A	B (1/ms)
Ponderosa pine litter	$0.97 - 0.19{*}Mf$	0.012
Punky wood (rotten, chunky)	$-0.59 - 0.15{*}Mf$	0.005
Punky wood powder (4.8 cm deep)	$1.2 - 0.12{*}Mf$	0.002
Punky wood powder (2.4 cm deep)	$0.13 - 0.05{*}Mf$	0.005
Lodgepole pine duff	$-5.6 + 0.68{*}d$	0.007
Douglas fir duff	$-7.1 * 1.4{*}d$	0.006
Englemann spruce mixed (high-altitude mixed)	$0.79 - 0.081{*}Mf - 8.5{*}\rho b$	0.011
Peat moss (commercial)	$0.42 - 0.12{*}Mf$	0.005

Mf is fuel moisture, % of dry weight; d is depth, cm; and ρb is bulk density (g/cm^3). The coefficient A is dimensionless, and B (ms^{-1}) multiplies the continuing current duration in milliseconds.

500 ms; the arc could not be maintained below 20 A, and 10 ms was a lower limit on the switch and arc initiation apparatus. A maximum current of 500 A and duration of 500 ms were chosen as high enough that extremely few continuing currents would exceed them.

Defining ignition was difficult. Pyrolysis of biomass materials unquestionably occurs at the edges of the lightning continuing current path, since pyrolysis results from temperatures near and above about 600 K (Susott, 1984), and the 7000–8000 K temperatures in the body of the arc (Figure 8) ablate the center material. Pyrolysis products from the material at the edge of the arc burn as linear diffusion flames, in which combustion depends on local fuel–air mixing rather than premixing as in a Bunsen burner flame (Cox, 1995).

Operationally, the difference between an ignition and a fire simply depends on whether or not the fire is seen and/or reported. Practically speaking, an ignition has taken place if the ignition source is sufficient to produce a self-sustaining combustion process once the source is gone. For the experimental results presented here, if the sample totally burned, or if smoldering continued after 5 min, an ignition was recorded.

B. Experimental Results

The experiments were designed to develop relationships between the independent variables and the probability of ignition. Independent variables for each fuel type for the ignition tests were arc current, arc duration, fuel moisture content, fuel bulk density, and fuel depth. For each set of conditions for a given fuel type, the result was either an ignition or not, a binary value. The results were tested using logistic regression, a systematic way of turning a binary result, such as the presence or absence of an ignition, into a probability of occurrence of the phenomenon (Loftsgaarden and Andrews, 1992). Typical results are plotted in Figures 14 and 15. The former is from one series of tests on Ponderosa pine litter; the latter is from Douglas fir duff. The regression process eliminated unimportant independent variables for each fuel type. One variable, arc current, was found unimportant, and arc duration was found to be most important, as conjectured by Fuquay *et al.* (1972). The unimportance of the arc current arises from the temperature structure of the arc channel, as developed in Section V.E. The most significant independent variable, after duration, is plotted on the ordinate for each of the fuel types. Lines of equal ignition probability as determined from the regression are also shown.

Figure 14 presents the results of tests on Ponderosa pine. The second most significant variable for this species was moisture content. Generally, as the moisture content increased, more energy, that is a greater current duration, was required to obtain ignition, as the regression probability lines indicate. No data

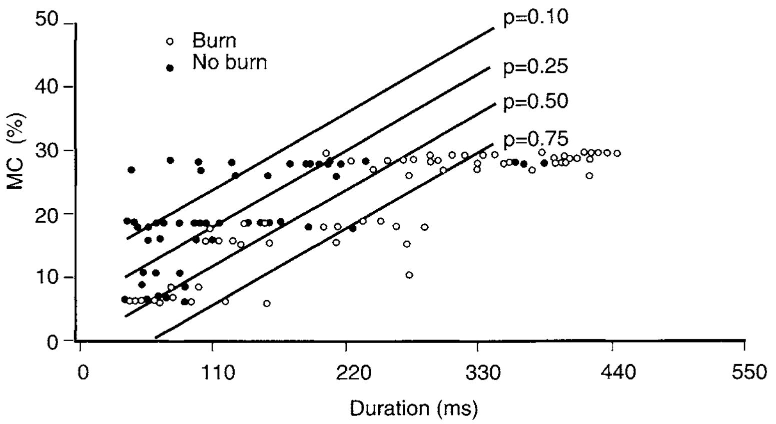

FIGURE 14 Ignition experiment data for Ponderosa pine needle fuel.

could be taken for moistures in excess of roughly 30% of dry weight because the woody material could not hold more moisture due to fiber saturation. Near fiber saturation, currents in excess of 400 ms invariably ignited the sample, and at the lower limit of the experiment, 8% moisture, currents of 50-ms duration ignited these fuels about 50% of the time.

Figure 15 shows the results of ignition tests on Douglas fir duff. For this species, the predominant secondary variable was, surprisingly, the depth of the fuel. Duff shallower than 2.8 cm did not ignite, and deeper samples ignited at small current duration, 50 ms.

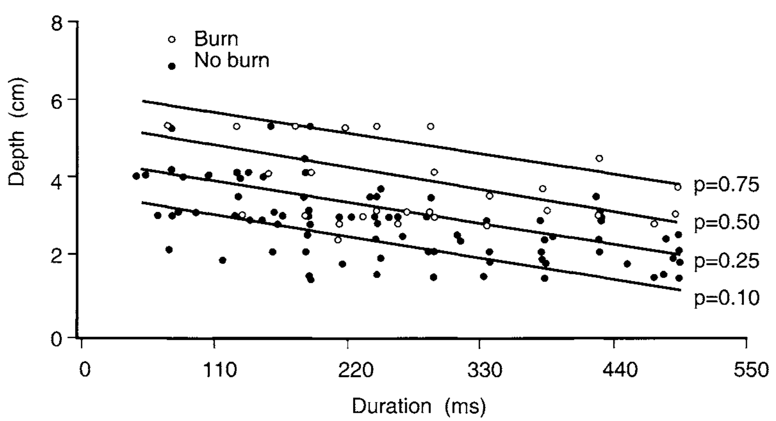

FIGURE 15 Ignition experiment data for Douglas fir duff beds.

An examination of samples that did not ignite demonstrated that the material in the high-temperature portion of the arc was ablated, as predicted from the temperatures calculated in Section V.E (Figure 8). Almost all samples with some soil showed fulgurites; glass was created from the melting of sand grains (2000 K) in the soil and dispersed through the fuels. The edges of the arc path through the fuels were charred. Clearly, the important mode of energy transfer was, as indicated previously by magnitude comparison, convective transport to fuel particles at the edge of the arc, as surmised in Section V.E. This means that the energy transferred to the material depended on the temperature structure of the edge of the arc, roughly the same for all central core temperatures (Figure 8) and durations.

The difference in the results implies a difference in heating mechanism between the more compact fuels, such as short-needled species duff (Figure 15), and the less compact litter of the long-needled species (Figure 14). In fact, the ignition probability for the former fuels did not depend on the fuel moisture or bulk density, and the latter depended on the moisture but not on bulk density or on depth.

Long-needled species litter is loosely arranged with large air spaces compared to the diameter of the needles. Short-needled species such as Douglas fir, on the other hand, have almost no litter layer, and the air spaces in the duff layer are small compared to the needle diameter. For this reason, the convection transfer to long-needled litter takes place to individual particles, and the transfer to short-needled litter takes place more in the form of the less-efficient wall transfer (Section V.E). Figure 15 shows that for Douglas fir duff less than about 2.8 cm deep, no ignitions occurred, even at fuel moisture content as low as 8% (a "very dry" duff moisture). So there may be an effect, in this dense fuel, of needing a "tube" to somehow constrain the arc in order to form a kind of muffle furnace effect (see also Chapter 13).

Ignition of spruce–fir samples having a mixed structure was dependent on both moisture and bulk density. No ignitions were observed for current durations on the order of 10 ms, and only one, in Ponderosa pine litter, at that value for fuel moisture of about 7%. Equipment limitations prevented current durations less than 10 ms. It is possible that, at least in some fuel types, currents shorter in duration than 10 ms can cause ignitions. Certainly many continuing currents are in the neighborhood of this duration (Thomson, 1980). Trends in the data for all species do show that as the current duration decreases, ignition probability decreases, and zero current should give no ignitions.

Frandsen (1987) showed that commercial peat moss, a reasonable surrogate for duff, could sustain smoldering combustion at moistures of 93–103% of dry weight. So the moisture content of the short-needled duff seems to be relatively unimportant in sustained combustion as well as in ignition. Meisner (1993) determined that the ignition efficiency in mixed fir fuels was 0.024 fires/CG flash, and the efficiency for Ponderosa pine fuel type was 0.042 fires/CG flash, about twice as large. This may be explained by the relative efficiency of heat transfer in the two fuel types. Further explanation would require further experiments. Application of logistic regression to the existing experimental results does, however, produce a useful application.

The form of the logistic regression equations obtained from the data is

$$pci(A, B, t) = [1 + \exp(-A - Bt)]^{-1} \tag{10}$$

where $pci(A, B, t)$ is the probability of ignition. A and B are coefficients depending on the experimental material, where A is dimensionless and B has dimension (ms^{-1}), and t is the continuing current duration in milliseconds (Table 1). Unfortunately, logistic regression implies a finite probability of ignition with zero continuing current duration, inconsistent with the lightning observations discussed in Section V.A. There may be a technique or formulation that will allow rectification of this shortcoming.

The consequences of the regression artifact are slight. The number of ignitions compared to nonignitions in the experiments for current duration near 10 ms is very small (see Figures 14 and 15). Also, the observations in Fuquay *et al.* (1972) show no fires caused by continuing currents with durations less than 40 ms and an average duration of 165 ms for those continuing currents starting fires. After an ignition event, the probability of fire growth can be obtained from fire data (Latham, 1979).

VII. GENERATING MODELS FOR OPERATIONAL USE

Using experimental results for operations requires knowledge of not only the fuel parameters for the locus of a strike but also the presence and duration of a continuing current in the strike. The fuel parameters are accessible in existing operational databases, and the location of the flash is known from lightning network data (to a claimed accuracy of 500 m), at least in the United States and parts of Canada.

A. Criteria for Utility

Although ignition models can provide ignition probabilities for most of the fuels found in forested and grassy landscapes, the models still have to be accommodated to reality. According to the models as presented, we can obtain an ignition probability if we know the kind of fuel present, its state (e.g., depth, moisture content, and bulk density), and the presence and duration of a continuing current.

Fortunately, lightning location systems now cover the United States and parts of Canada. Unfortunately, the location data cannot give either the duration of a continuing current or even the presence of one. ELF methods are well suited to identifying and quantifying the continuing current (Burke and Jones, 1996; Huang *et al.*, 1999), but these methods are presently not applicable to operations. There are, however, statistics for the probability distribution of the duration of continuing currents in both positive and negative discharges, as well as the probability that a flash has a stroke with a continuing current (Latham and Schlieter, 1989). The statistics we use are valid for thunderstorms in the northern Rocky Mountains.

B. Probability Distributions for Continuing Currents

Application of the ignition equations requires knowledge of continuing current durations on a flash-by-flash basis. The statistics of continuing current durations have been generally thought to be lognormal (e.g., Cianos and Pierce, 1972), although Thomson (1980) found that a lognormal distribution assumption for continuing current durations failed a χ^2 test. Other distributions might work as well and are more tractable for mathematical manipulation. The Weibull is a two-parameter distribution that is the statistic of choice for failure of a whole unit contingent on the failure of a part or parts of the whole (Hahn and Shapiro, 1967). This viewpoint is attractive in that it might correspond to a continuing current channel fed by subchannels in the cloud. Weibull and lognormal distributions were each fit to continuing current duration data from the Skyfire experiments (Fuquay and Baughman, 1969), covering 141 negative hybrid flashes (duration between 20 and 520 ms) and 54 positive flashes. The two resulting distributions were tested according to a method developed by Kappenman (1988). The Weibull distribution was found to better describe the measurements. According to the Weibull fit, the distribution

$$p(t, n, s) = \left(\frac{n}{s}\right)\left(\frac{t}{s}\right)^{n-1} \exp\left[-\left(\frac{t}{s}\right)^{n}\right] \tag{11}$$

generates probability distribution functions, p, for continuing current duration, t in milliseconds, with the parameters $n = 1.6$, $s = 207.8$ for negative currents, and $n = 2.3$, $s = 69.3$ for positive currents. These coefficients have no physical interpretation. The distributions are shown in Figure 16 and are valid for thunderstorms in the northern Rocky Mountains. Thomson's (1980) results for Port Moresby show that there are certainly continuing current durations less than

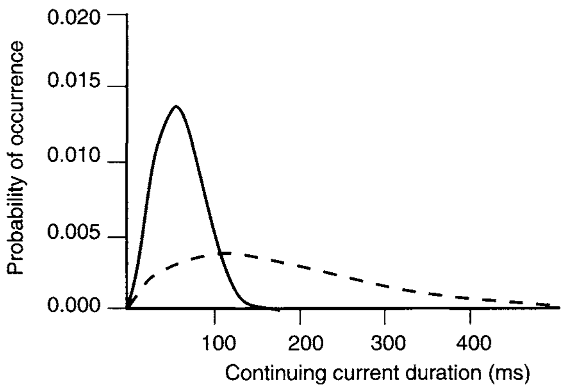

FIGURE 16 Probability distributions for negative (dashed) and positive (solid) continuing currents.

20 ms but, as the experiments summarized in Section VI show, extremely few ignitions are observed for durations less than 20 ms and none below 10 ms for laboratory experiments.

C. Conditional Probability of Ignition

Because the probability distribution function for continuing currents is known, ignorance of the characteristics of any given continuing current can be dealt with using conditional probability. The probability of occurrence of an ignition is dependent on several parameters. If a statistical description of one of the parameters, such as current duration, is known, the parameter can be effectively removed from the parameter list by integrating the probability of occurrence over the probability distribution of the parameter. In the present case, integration allows calculation of the probability of ignition per continuing current for known fuel parameters. The probabilities of ignition were given in Table 1, and the probability distributions for continuing currents in Section VII.B.

The conditional probability for lightning ignition is calculated using the integral

$$p_i(n, s, A, B) = \int_0^\infty p(t, n, s)\, pci(A, B, t)\, dt \tag{12}$$

where $p_i(n, S, A, B)$ is the probability density for ignition per continuing current event (between 0 and 1), A and B are coefficients from Table 1, and t is du-

TABLE 2 Conditional Probabilities for Ignition of Fuel Types Used in the Ignition Experiments

Fuel	Pi neg	Pi pos
Ponderosa pine litter	1.04 exp(−0.054*Mf*)	0.92*exp(−0.087**Mf*)
Punky wood (rotten, chunky)	0.59*exp(−0.094**Mf*)	0.44*exp(−0.11**Mf*)
Punky wood powder (4.8 cm deep)	0.9*exp(−0.056**Mf*)	0.86*exp(−0.06**Mf*)
Punky wood powder (2.4 cm deep)	0.73 − 0.011**Mf*	0.6 − 0.11**Mf*
Lodgepole pine	1.0/[1 +exp(3.84 − 0.6**d*)]	1.0/[1 + exp(5.13 − 0.68**d*)]
Douglas fir	1.0/[1 + exp(5.48 − 1.28**d*)]	1.0/[1 + exp(6.69 − 1.39**d*)]
Englemann spruce (subalpine)	0.8 − 0.014**Mf*	0.62*exp(−0.05**Mf*)
Peat moss (commercial)	0.84*exp(−0.058**Mf*)	0.71*exp(−0.72**Mf*)

Mf is fuel moisture, % of dry weight, and *d* is depth, cm.

ration in milliseconds. The final form of this ignition probability, in approximation, is given in Table 2.

Based on similarity of forest floor and tree characteristics, the results of the conditional probability estimates can be applied to other species (Latham and Schlieter, 1989).

D. Implementation of Ignition Probability

Figure 17 shows one way to implement the ignition probabilities into an operational system. In this scheme, a Geographic Information System map layer for ignition probability per positive and per negative lightning flash is generated using the algorithms developed in the last section. As the lightning location data come in, the location is binned into pixels that correspond to the ignition probability layer. The combination of the two becomes a projected fires layer. This scheme has not been implemented. A somewhat simpler scheme is presently employed. Lightning locations are aggregated into 1-hr files. The files are made available to dispatch users. Since the locations are points, they are used as an overlay on many different maps, including ignition efficiency, fuel type, terrain, or any other desired layer. Implementation of more sophisticated schemes is a goal for future studies.

Ignition probability information can also be used in gaming and forecasting as well as combined with forest growth programs. These uses have yet to be implemented.

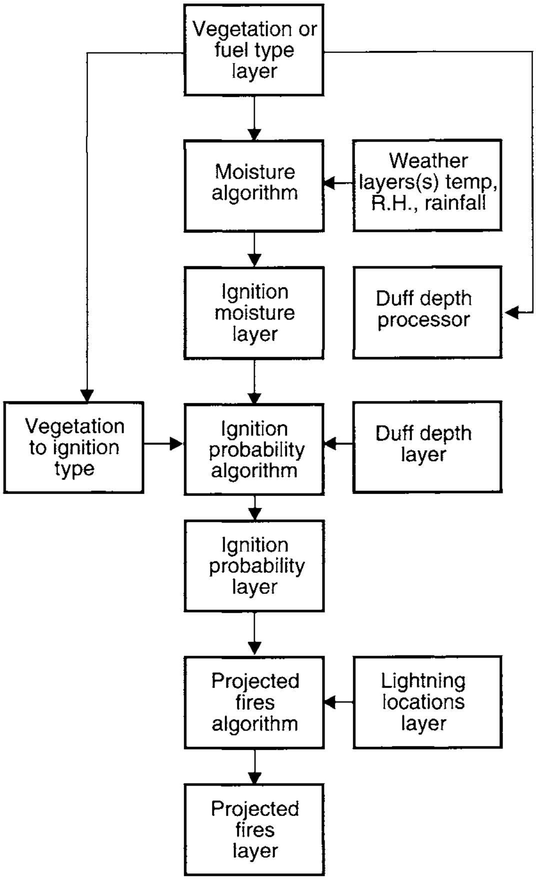

FIGURE 17 Operational diagram for ignition use of probabilities.

VIII. SMOKE, LIGHTNING, AND CLOUD MICROPHYSICS

Large-scale networks for cloud-to-ground lightning detection have disclosed an intriguing coupling between forest fires and the electrification of thunderstorms within their range of influence. As emphasized in Section II, the great majority of ordinary thunderstorms produce ground flashes with negative polarity. Within the last 20 years, several authors (Vonnegut and Orville, 1988; Latham, 1991; Vonnegut, *et al.*, 1995; Lyons *et al.*, 1998a) have documented a shift from negative to positive ground flash prevalence in association with forest fires and forest fire smoke.

At present, it is not known whether a single mechanism will afford an explanation for these several observations with different attendant conditions. When aerosol in fire smoke is ingested in a convective storm, complexity rises in areas of chemistry, cloud microphysics, and electrification. In line with these complications, multiple explanations have been put forward for the observations cited in the previous paragraph. Latham (1991) suggested a thunderstorm whose main dipole is inverted with respect to the usual positive dipole. Vonnegut *et al.* (1995) made a case for an influence-charging mechanism, with ingestion of negative space charge in the fire smoke (Latham, 1999) leading to an inverted polarity cloud. Lyons *et al.* (1998a) also considered an influence mechanism to explain their observations but discounted it because the anomalous thunderstorms they observed, though ingesting fire smoke, were more than 1000 km from the source of the smoke, casting doubt on the persistence of appreciable space charge. Lyons *et al.* (1998a) did call attention to the effect of aerosol smoke on cloud condensation and on the size of cloud droplets, with more numerous smaller droplets accompanying smoke ingestion by the cloud, an effect documented at the cloud scale in satellite observations (Kaufman and Nakajima, 1993; Rosenfeld and Lensky, 1998), and more recently by *in situ* observations (Reid *et al.*, 1999). Recent laboratory simulations (Avila *et al.*, 1998) suggest that strong positive charging of graupel particles might occur in the presence of small cloud droplets, resulting in an inverted polarity cloud, perhaps conducive to positive ground flashes. Harvey and Edwards (1991) theorized that the collection efficiency of smoke by droplets is enhanced if the smoke particles are charged.

Clearly, *in situ* measurements of clouds ingesting fire smoke are needed to shed further light on physical mechanisms. Two interesting feedback effects associated with the fire smoke/cloud coupling add incentive to such studies. First, if clouds ingesting smoke produce large numbers of positive ground flashes, and if these ground flashes exhibit the continuing currents typical of other positive flashes, then the forest fire threat is exacerbated. In fact, the Red Lake #7 fire in Canada grew a cloud that produced lightning, starting six additional fires (Stocks and Flannigan, 1987). Second, given the evidence that smoke ingestion by deep convection decreases cloud droplet size (Reid *et al.*, 1999), it is likely that droplet coalescence will be suppressed with the effect of a lower precipitation yield (Schaefer and Day, 1981) to aid in dousing the fire naturally.

IX. GLOBAL IMPLICATIONS OF LIGHTNING IGNITION CHARACTERISTICS

Global maps of lightning and forest fire incidence are shown in Figures 18 and 19, respectively (see color insert) (S.Goodman and H. Christian, personal communication, 1999; Dwyer *et al.*, 1999). As emphasized earlier in this chapter, both lightning and flammable forest fuel are required for ignition of natural fire. The areas of most prevalent lightning are the tropical continental zones—Southeast Asia, Northern Australia, Africa, Central and South America. Forests are also prevalent in these zones but as rainforests, with precipitation in abundance, flora with high moisture content, and ground beneath the rainforest canopy often completely inundated. The latter condition is likely to suppress the most common fire initiation mechanism at midlatitude (described in Sections IV and V). This claim appears to be supported by the near equatorial zones of minimum fire activity in Africa and South America, where the intertropical convergence zone is likely on an annual basis, and where lightning activity is a maximum. The majority of fires within these tropical zones are slightly displaced from the equatorial regions and are set intentionally in the respective dry seasons (associated with large-scale subsidence of the equatorial Hadley circulation) to burn back the flora of the previous wet season and prepare for crop planting.

The desert areas of the subtropics, the more permanent areas of large-scale subsidence from the intertropical convergence zone (e.g., the African Sahara, the Mexican Sonoran desert, the Chilean desert, the Namibian desert, the central area of Australia) lack both forest fuel and the moist convection necessary for lightning. As a consequence, these areas are largely devoid of naturally caused fire.

The northern boreal forests, heavily populated with flammable conifers, also experience a moderately high incidence of lightning. In fact, the observations with the Optical Transient Detector in space (Figure 18) showed a surprisingly high incidence of lightning in all mid-to-high latitude land regions [e.g., northern Canada, northern Russia (Siberia)]. Fires in a huge area of northern Russia are increasingly well documented by satellite (Kasischke *et al.*, 1999). Much of the lightning in this region had evidently been missed in earlier space-based observations (e.g., Orville and Henderson, 1986) because of the sustained daylight into the late evening at this high latitude that interferes with the optical detection of flashes (S. Goodman, personal communication 1998).

Northwestern North America, including British Columbia, is watered by ocean air mass coming in off the Pacific Ocean, dropping rain on the mostly fire-impervious high biomass density on the western slopes of the coastal mountains. The eastern slopes, on the other hand, have a generally lower biomass density, due to lower overall rainfall, but a higher lightning ignition probability, and hence more fires. The Rocky Mountains get winter snowfall that provides necessary moisture for forests and dry summers that generally cause high ignition efficiencies (Section IV.C). The forests of the American southwest, up into Utah, generally receive moisture from air from the Gulf of Mexico during the thunderstorms that arise in the summertime. The lightning fire season in this area is in the early summer (May and June), whereas the fire season in the northern Rockies is late in the summer (July and August).

Suppression of fires started by natural ignitions in this region causes fuel build-up and eventually ecosystem conversion to unhealthy forest. Natural ignition under these unhealthy conditions will eventually cause large, uncontrollable fires. Application of lightning ignition probabilities can be useful for identifying those areas that are prone to high lightning ignition probability and help decide where fires should be started, and where natural ignition can be helpful. When used in conjunction with lightning location, ignition efficiencies can indicate areas that are likely to have large numbers of holdover fires.

Moving eastward in North America, central Canada and the United States have vast cropland and very little timber. The ignition efficiency for grass is lower, and much of the area is irrigated; lightning-caused fire is of little importance even though lightning densities are high. Further east, deciduous forests have shaded, moist, dense forest floors, with concomitant low ignition efficiency. Peak fire periods are spring and fall, with few fires in the summer. The southeast is forested, but there are relatively few lightning-caused fires because of moist fuels. Lightning fires do occur in the Everglades peat (Sections V.D and VI.B).

Lightning ignition considerations were used to calculate the effect of global warming on lightning caused fires (Price and Rind, 1994). The results showed that, under a scenario of CO_2 doubling, lightning fires would increase by 30–77%, depending on the region of the United States considered. The calculations were made under the assumption that the ecosystems did not change, that is, that the fuels were constant over time. If there were a considerable increase of fires, there would be a fuel change. As with many calculations of this type, there are uncontrolled variables and no data. (See Chapter 10 in this book for more discussion of the climate issue.)

X. CONCLUSION

Lightning ignition of wildland fuels plays a major role in the maintenance and evolution of ecosystems. In this chapter, we have discussed the predominant mechanism for lightning ignition and how this knowledge can be used in fire management. There is little doubt, based on theoretical approaches, laboratory experiments, and global fire and lightning data, that the fuel type and fuel state play a much larger role than the lightning density in lightning fire ignitions. The efficiency of lightning fires seems to be in the range of 0.01–0.04 fires/CG flash in much of North America; that is, only about one to four flashes in 100 start fires. It remains to be seen whether these efficiencies are larger in other places. Certainly, in central Africa and South America, efficiencies are much lower; how much lower we have no way of knowing at present.

As we have seen, lightning fires can act upon the lightning environment through smoke, even inverting the charge structure of thunderstorms. Again, the exact mechanism remains a mystery, and there may be more than one mechanism at work. Charge separation occurs due to flaming in the presence of electric fields, and the smoke carrying that charge is carried into local pyrocumulus. That charge may not remain on the smoke particles for long, however, and inverted storms in regions far from the smoke origin in space and time may be due only to the presence of smoke particles and their interaction with thunderstorm-charging mechanisms. Finally, lightning ignition of fires may or may not have a role in ecosystems altered by climate change.

REFERENCES

Adams, P. (1966). High-temperature, equilibrium thermodynamic properties of chemically reacting mixture of N_2, O_2, CO_2, A, and Ne. Aerospace Tech. Rept. 9, Hughes Corp., Los Angeles.

Avila, E., Caranti, G., Castellano, N., and Saunders, C. (1998). Laboratory studies of the influence of cloud droplet size on charge transfer during crystal-graupel collisions. *J. Geophys. Res.* **103**, 8985–8996.

Barrows, J. S. (1954). Lightning fire research in the Rocky Mountains. *J. For.* **52**, 845–847.

Barrows, J. S., Deterich, J. H., Odell, C. A., Kaehn, C. H., Fuquay, D. M., Schaefer, V. J., MacCready Jr., P. B., Colson, D., and Wells, H. J. (1958). Project Skyfire. *In* "Final Report of the Advisory Committee on Weather Control," Vol. II, pp. 105–125. U.S. Government Printing Office, Washington, DC.

Barrows, J. S., Sandbert, D. V., and Hart, J. D. (1977). "Lightning Fires in Northern Rocky Mountain Forests." Final Report, Cooperative Agreement 16-440-CA. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden.

Baughman, R.G., Fuquay, D. M., and Mielke Jr., P. W. (1976). Statistical analysis of a randomized lightning modification experiment. *J. Appl. Meteorol.* **15**, 790–794.

Berger, K. (1947). Lightning research in Switzerland. *Weather* **2**(8), 231–238.

Boccippio, D. J., Williams, E. R., Heckman, S. J., Lyons, W. A., Baker, I. T., and Boldi, R. (1995). Sprites, ELF transients, and positive ground strokes. *Science* **269**, 1088–1091.

Boccippio, D. J., Cummins, K., Christian, H. J., and Goodman, S. J. (2001). Combined satellite and surface-based estimation of the intracloud/cloud-to-ground lightning ratio over the continental United States. *Mon. Weath. Rev.*, in press.

Burke, C. P., and Jones, D. L. (1996). On the polarity and continuing current in unusually large lightning flashes deduced from ELF events. *J. Atmos. Terrestr. Physics* **58**, 531–548.

Cianos, N., and Pierce, E. T. (1972). "A Ground-lightning Environment for Engineering Usage." Tech. Rep. 1, SRI Project 1834. Stanford Research Institute, Menlo Park.

Connor, T. R. (1967). "The 1965 ARPA-AEC Joint Lightning Study at Los Alamos." Publ. LA-3754, Vol. 1. Los Alamos Scientific Laboratory, Los Alamos.

Cox, G., Ed. (1995). "Combustion Fundamentals of Fire." Academic Press, London.

Cummer, S. A., and Inan, U. S. (1996). Sprite-producing lightning using ELF radio atmospherics. *Geophys. Res. Lett.* **24**, 1731–1734.

Cummins, K. L., Murphy, M. J., Bardo, E. A., Hiscox, W. L., Pyle, R. B., and Pifer, A. E. (1998). A combined TOA/MDF technology upgrade of the U.S. national lightning detection network. *J. Geophys. Res.* **103**, 9035–9044.

Darveniza, M. (1980). "Electrical Properties of Wood and Line Design." University of Queensland Press, St. Lucia.

Darveniza, M., and Zhou, Y. (1994). Lightning-initiated fires: Energy absorbed by fibrous materials from impulse current arcs. *J. Geophys. Res.* **99**, 10663–10670.

Deeming, J. E., Burgan, R. E., and Cohen, J. D. (1977). "The National Fire Danger Rating System—1978." Gen. Tech. Rep. INT-39. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden.

Defandorf, F. M. (1955). A tree from the viewpoint of lightning. *J. Wash. Acad. Sci.* **45**, 333–339.

Dennis, A. S. (1980). "Weather Modification by Cloud Seeding." Academic Press, New York.

Du Moncel, T. (1877). Recherches sur la conductibilite electrique des corps mediocrament conducteurs et les phenomenes qui les accompagnet. *Annales de Chimie et de Physique* [vol.?], 471.

Dwyer, E., Pereira, J. M. C., Gregoire, J-M., and DaCamara, C. C. (1999). Characterization of the spatio-temporal patterns of global fire activity using satellite imagery for the period April 1992 to March 1993. *J. Biogeog.*, in press.

Flannigan, M. D., and Wotton, B. M. (1991). Lightning-ignited fires in northwestern Ontario. *Can. J. For. Res.* **21**, 277–287.

Frandsen, W. H. (1987). The influence of moisture and mineral soil on the combustion limits of smoldering forest duff. *Can. J. For. Res.* **17**, 1540–1544.

Fuquay, D. M. (1974). Lightning damage and lightning modification caused by cloud seeding. *In* "Weather and Climate Modification" (W. N. Hess, Ed.), pp. 604–612. Wiley, New York.

Fuquay, D. M., and Baughman, R. G. (1969). "Project Skyfire Lightning Research." Final Report to the National Science Foundation, USDA Forest Service, Intermountain Forest and Range Experiment Station, Missoula.

Fuquay, D. M., Baughman, R. G., Taylor, A. R., and Hawe, R. G. (1967). Characteristics of seven lightning discharges that caused forest fires. *J. Geophys. Res.* **72**, 6371–6373.

Fuquay, D. M., Taylor, A. R., Hawe, R. G., and Schmidt Jr., C. W. (1972). Lightning discharges that started forest fires. *J. Geophys. Res.* **77**, 2156–2158.

Gisborne, H. T. (1924). Lightning fires and storms in the northern Rocky Mountains. *In* "The Timberman," p. 2. Portland.

Gisborne, H. T. (1926). Lightning and forest fires in the northern Rocky Mountains. *Mon. Weath. Rev.* **54**, 281–286.

Gisborne, H. T. (1931). A five-year record of lightning storms and forest fires. *Mon. Weath. Rev.* **59**, 139–150.

Greig, J. R., Pechacek, R. E., and Raleigh, M. (1985). Channel cooling by turbulent convective mixing. *Physics of Fluids* **28**, 2357–2364.

Hahn, G. J., and Shapiro, S. S. (1967). "Statistical Models in Engineering." John Wiley and Sons, New York.

Harvey, T. F., and Edwards, L. L. (1991). A parametric investigation of electrical effects on aerosol scavenging by droplets over large fires. *Atmos. Environ.* **25A**, 2607–2614.

Huang, E., Williams, E., Boldi, R., Lyons, W., Nelson, T., Taylor, M., Heckman, S., and Wong, C. (1999). Criteria for sprites and elves based on Schumann resonance measurements. *J. Geophys. Res.* **104**, 1693–1694.

Incropera, F. P., and DeWitt, D. P. (1996). "Fundamentals of Heat and Mass Transfer," 4th ed. John Wiley and Sons, New York.

Jones, J. C., Ramahti, H., Fowler, D., Vorasurayakarnt, J., and Bridges, R. G. (1990). The self heating and thermal ignition propensity of forest floor litter. *J. Fire Sci.* **8**, 207–223.

Kappenman, R. F. (1988). A simple method for choosing between the lognormal and Weibull distributions. *Stat. Prob. Lett.* 7 (Sept), 123–126.

Kasischke, E. S., Bergen, K., Fennimore, R., Sotelo, F., Stephens, G., Janetos, A., and Shugart, H. H. (1999). Satellite imagery gives clear picture of Russia's boreal forest fires. *EOS* **80**, 141.

Kaufman, Y. J., and Nakajima, T. (1993). Effect of Amazon smoke on cloud microphysics and albedo analysis form satellite imagery. *J. App. Meteorol.* **32**, 729–744.

King, L. A. (1961). "The Voltage Gradient of the Free-burning Arc in Air or Nitrogen." ERA Rep. G/XT172. The British Electrical and Allied Industries Research Association, Leatherhead.
Latham, D. J. (1979). "Progress Toward Locating Lightning Fires." Res. Note INT-269. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden.
Latham, D. J. (1984). A numerical simulation of the lightning continuing current channel. *In* "Proceedings, Seventh International Conference on Atmospheric Electricity," pp. 417–420. American Meteorological Society, Boston.
Latham, D. J. (1986). Anode column behavior of long vertical air arcs at atmospheric pressure. *IEEE Trans. Plasma Sci.* **PS-14**, 220–227.
Latham, D. J. (1987). "Design and Construction of an Electric Arc Generator for Fuel Ignition Studies." Res. Note INT-366. USDA Forest Service, Intermountain Research Station, Ogden.
Latham, D. J. (1989). "Characteristics of Long Vertical DC Arc Discharges." Res. Pap. INT-407. USDA Forest Service, Intermountain Research Station, Ogden.
Latham, D. J. (1991). Lightning flashes from a prescribed fire-induced cloud. *J. Geophys. Res.* **96**, 17151–17157.
Latham, D. J. (1999). Space charge generated by wind tunnel fires. *Atmos. Res.* **51**, 267–278.
Latham, D. J., and Schlieter, J. A. (1989). "Ignition Probabilities of Wildland Fuels Based on Simulated Lightning Discharges." Res. Pap. INT-411. USDA Forest Service, Intermountain Research Station, Ogden.
Ligda, M. G. H. (1956). The radar observation of lightning. *J. Atmos. Terr. Phys.* 9, 329–346.
Loeb, L. B. (1966). The mechanisms of stepped and dart leaders in cloud-to-ground lightning strokes. *J. Geophys. Res.* **71**, 4711–4721.
Loftsgaarden, D. O., and Andrews, P. A. (1992). "Constructing and Testing Logistic Regression Models for Binary Data: Applications to the National Fire Danger Rating System." Gen. Tech. Rep. INT-286. USDA Forest Service, Intermountain Research Station, Ogden.
Lyons, W. A., Nelson, T. E., Williams, E. R., Cramer, J. A., and Turner, T. R. (1998a). Enhanced positive cloud-to-ground lightning in thunderstorms ingesting smoke from fires. *Science* **282**, 77–80.
Lyons, W. A., Uliasz, M., and Nelson, T. E. (1998b). A climatology of large peak current cloud-to-ground lightning flashes in the contiguous United States. *Mon. Weath. Rev.* **126**, 2217.
Malan, D. J. (1963). "Physics of Lightning." English University Press, London.
Martin, S., and Broido, A. (1963). "Thermal Radiation and Fire Effects of Nuclear Detonations." Rep. AD 422411. U.S. Naval Radiological Defense Laboratory, San Fransisco.
Mazur, V., Shao, X. M., and Krehbiel, P. (1998). "Spider" lightning in intracloud and positive cloud-to-ground flashes. *J. Geophys. Res.* **D16**, 19811–19822.
McEachron, K. B., and Hagenguth, J. H. (1942). Effect of lightning on thin metal surfaces. *AIEE Trans.* **61**, 559–564.
McMullen, L. H., and Atkins, M. D. (1962). On the flight and host selection of the Douglas-fir beetle *Dendroctomus pseudotsugae* Hopk. (Coleoptera: Scolytidae). *Can. Entomol.* 94, 1309–1325.
McRae, R. H. D. (1992). Prediction of areas prone to lightning ignition. *Int. J. Wildl. Fire* **2**, 123–130.
Meisner, B. N. (1993). "Correlation of National Fire Danger Rating System Indices and Weather Data with Fire Reports." Final Report, Interagency Agreement No. R500A20021. USDA Forest Service, Forest Fire Laboratory, Pacific Southwest Research Station, Riverside.
Melosh, H. J., Schneider, N. M., Zahnle, K. J., and Latham, D. J. (1990). Ignition of global wildfires at the Cretaceous/Tertiary boundary. *Nature* **343**, 251–254.
Morris, W. G. (1934). "Lightning Storms and Fires on the National Forests of Oregon and Washington." USDA Forest Service, Pacific Northwest Forest Experiment Station, Portland.
Nash, C. H., and Johnson, E. A. (1996). Synoptic climatology of lightning-caused forest fires in subalpine and boreal forests. *Can. J. For. Res.* **26**, 1859–1874.

Orville, R. E., and Helsdon Jr., J. H. (1974). Quantitative analysis of a lightning return stroke for diameter and luminosity changes as a function of time. *J. Geophys. Res.* 79, 4059–4067.

Orville, R. E., and Henderson, R. W. (1986). Global distribution of midnight lightning: September 1977 to August 1978. *Mon. Wea. Rev.* **114**, 264–2653.

Plummer, F. G. (1912). "Lightning in Relation to Forest Fires." Bulletin 111. USDA Forest Service, Government Printing Office, Washington, DC.

Price, C., and Rind, D. (1994). The impact of a $2xCO_2$ climate on lightning-caused fires. *J. Climate* 7, 1484–1494.

Reid, J. S., Hobbs, P. V., Ragno, A. L., and Hegg, D. A. (1999). Relationships between cloud droplet effective radius, liquid water content, and droplet concentration for warm clouds in Brazil embedded in biomass smoke. *J. Geophys. Res.* **104**, 6145–6153.

Renkin, R. A., and Despain, D. G. (1992). Fuel moisture, forest type, and lightning-caused fire in Yellowstone National Park. *Can. J. For. Res.* **22**, 37–45.

Rorig, M. L., and Ferguson, S. A. (1999). Characteristics of lightning and wildland fire ignition in the Pacific Northwest. *J. Appl. Met.* **38**, 1565–1575.

Rosenfeld, D., and Lensky, I. (1998). Satellite-based insights into precipitation formation processes in continental and maritime convective clouds. *Bull. Amer. Meteorol. Soc.* 79, 2457–2476.

Salanave, L. E. (1965). The photographic spectrum of lightning: Determination of channel temperature from slitless spectra. *In* "Problems of Atmospheric and Space Electricity" (S. C. Coriniti, Ed.), pp. 371–384. Elsevier Publishing Company, New York.

Schaefer, V. J. (1949). "The Possibility of Modifying Lightning Storms in the Northern Rockies." Pap. No. 19. USDA Forest Service, Northern Rocky Mountain Forest and Range Experiment Station, Missoula.

Schaefer, V. J. (1953). "Final Report Project Cirrus, Part 1." Report No. RL-785. General Electric Research Laboratory, Schenectady.

Schaefer, V. J., and Day, J. A. (1981). "A Field Guide to the Atmosphere." Houghton Mifflin and Co., Boston.

Schmitz, R. F., and Taylor, A. R. (1969). "An Instance of Lightning Damage and Infestation of Ponderosa Pines by the Pine Engraver Beetle in Montana." Res. Note INT-88. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden.

Schonland, B. F. J., and Collens, H. (1934). Progressive lightning. *Proc. Roy. Soc. (Lond)* A143, 654–674.

Sentman, D. D. (1987). *EOS 67 (suppl.)* 67, 1069.

Simms, D. L., and Law, M. (1967). The ignition of wet and dry wood by radiation, *Combust. Flame* **11**, 377–388.

Stocks, B. J., and Flannigan, M. D. (1987). Analysis of the behaviour and associated weather for a 1986 northwestern wildfire: Red Lake #7. *In* "Proceedings, Ninth Conference on Fire and Forest Meteorology," pp. 94–99. American Meteorological Society, Boston.

Strachan, D. C., and Barrault, M. R. (1975). "Axial Velocities in the High Current Free Burning Arc." Rep. ULAP-T34. Department of Electrical Engineering and Electronics, University of Liverpool, Liverpool.

Strom, A. P. (1946). Long 60-cycle arcs in air. *AIEE Trans.* 65, 113–117.

Susott, R. A. (1984). "Heat of Preignition of Three Woody Fuels Used in Wildfire Modeling Research." Res. Note INT-342. USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden.

Taylor, A.R. (1969). Lightning effects on the forest complex. *In* "Proceedings, Annual Tall Timbers Fire Ecology Conference," pp. 127–150. Tall Timbers Research Station, Tallahassee.

Taylor, A. R. (1973). Ecological aspects of lightning in forests. *In* "Proceedings, Annual Tall Timbers Fire Ecology Conference," pp. 455–482. Tall Timbers Research Station, Tallahassee.

Thomson, E. M. (1980). Characteristics of Port Moresby ground flashes. *J. Geophys. Res.* **85**, 1025–1036.

Uman, M. A. (1969). "Lightning." McGraw-Hill, New York.

Uman, M. A., and Voshall, R. E. (1968). Time interval between lightning strokes and the initiation of dart leaders. *J. Geophys. Res.* **73**, 497–506.

Van Wagner, C. E. (1987). "Development and Structure of the Canadian Forest Fire Index System." Tech. Rep. 35. Canadian Forestry Service, Ottawa.

Van Wagtendonk, J. W. (1991). Spatial analysis of lightning strikes in Yosemite National Park. *In* "Proceedings, Eleventh Conference on Fire and Forest Meteorology," pp. 605–611. American Meteorological Society, Boston.

Vonnegut, B., and Orville, R. E. (1988). Evidence of lightning associated with the Yellowstone Park forest fire (abstract). *EOS Trans. AGU* **69**, 1071.

Vonnegut, B., Latham, D. J., Moore, C. B., and Hunyady, S. J. (1995). An explanation for anomalous lightning from forest fire clouds. *J. Geophys. Res.* **100**, 5037–5050.

Williams, E. R. (1989). The tripole structure of thunderstorms. *J. Geophys. Res.* **94**, 13151–13167.

Williams, E. R. (1998). The positive charge reservoir for sprite-producing lightning. *J. Atmos. Terr. Phys.* **60**, 689–692.