Impacts of Meteorological Factors on MODIS-Observed Fire Activity in the North American Boreal Forest: The Role of Lightning

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IMPACTS OF METEOROLOGICAL FACTORS ON MODIS-OBSERVED FIRE ACTIVITY IN THE NORTH AMERICAN BOREAL FOREST: THE ROLE OF LIGHTNING

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The meteorological impact on wildfire activity in the North American boreal forest during the fire seasons of 2000 – 2006 is statistically analyzed through an integration of the following data sets: the MODerate Resolution Imaging Spectroradiometer (MODIS) level 2 fire products, the 3-hourly 32-km gridded meteorological data from North American Regional Reanalysis (NARR), the instantaneous lightning data collected by the Canadian Lightning Detection Network (CLDN), and the Alaska Lightning Detection Network (ALDN). Positive anomalies of the 500 hpa geopotential height field, convective available potential energy (CAPE), number of cloud-to-ground lightning strikes, and the number of consecutive dry days are found to be statistically important to the monthly variation of MODIS fire counts in portions of Canada and the entirety of Alaska. It is revealed that dry lightning strikes account for only 20% of the total lightning strikes, but they are associated with (and likely cause) 40% of the MODIS observed fire counts in the Alaskan and Canadian boreal forest regions. Analysis of fire occurrence patterns in two sub-regions of the North American boreal forest shows that a higher probability for dry lightning occurs only when 500 hPa geopotential heights are above ~ 5700 meters and CAPE values are near the maximum observed level, underscoring the importance of low-level instability to
the boreal fire weather indices. In contrast, the higher probability for wet lightning is spread over a large range of CAPE values. Locations with a high percentage of dry strikes commonly experience an increased number of fire counts, while the mean number of fire counts per dry strike is more than 50% higher in western boreal forest, suggesting a geographic and possible topographic influence. Furthermore, the combination of at least 10 dry strikes per grid and at least 10 consecutive dry days is found to be an important threshold to increase fire activity.
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1. Introduction and Background

The boreal forest of North America, which is dominated by dense evergreen vegetation, covers an east-west oriented belt of land south of the tundra regions, and is a favorite spawning ground for wildfire activity each summer (Ichoku et al., 2008a). With plenty of available fuel to burn, wildfires often reach 200 hectares in size and are commonly left to burn unimpeded because of their remoteness (Stocks et al., 2002). In Alaska alone, over 2.70 million hectares burned from 1990 to 1996 (Dissing and Verbyla, 2003). In the large boreal forest in Canada, a similar average of 2.75 million hectares was found to burn annually during the 1990s (Stocks et al., 2002). In addition to the ecological health hazard and change in surface albedo caused by biomass burning, enormous amounts of particulate matter, as well as carbon monoxide, carbon dioxide, methane, and other trace gases are ejected into the atmosphere, creating concerns for air quality and other atmospheric impacts (e.g. Spracklen et al., 2007; Jordan et al., 2008). The need for an accurate assessment of direct and indirect fire impacts including the development of effective mitigation strategies underscores the importance of studying the potential causes of wildfire ignition in the boreal region.

Attempts have been made in past decades to discern the role of local meteorology, topography, climate, and land use in the formation of intense boreal fire seasons (e.g. Skinner et al., 1999; Stocks et al., 2002). Flannigan and Harrington (1988) described the enhanced effect of prolonged dry and warm periods on fire intensity and duration. Skinner et al. (1999, 2002) showed that regions under the influence of positive 500 hPa geopotential height anomalies in Canada commonly experience above average fire
seasons (Fig. 1). In addition, Fauria and Johnson (2006) discovered that positive height anomalies must persist for approximately 10 days to have a significant impact on fire activity. These earlier studies suggest that persistent positive height anomalies result in a warmer and drier atmosphere with enough convective activity present for the production of isolated lightning events that ignite fires.

Lightning strikes are common in the interior regions of the North American boreal forest and have a positive correlation with elevation. In Alaska, Reap (1991) found a positive relationship with lightning strikes and elevations up to 800 meters, while Dissing and Verbyla (2003) found a similar positive relationship up to 1200 meters. Quantitatively, Boles and Verbyla (2000) discovered that 93% of the land burned in Alaska during 1990-1996 was a result of lightning-started fires, and Stocks et al. (2002) found that ~72% of the large fires in Canada during 1959-1997 were associated with lightning activity. These fires are sparked by thunderstorms producing “dry” lightning, which can occur by any of the following scenarios: (a) the thunderstorm is high-based and most of the precipitation evaporates before reaching the ground; (b) lightning strikes outside the rain shaft of a “wet” thunderstorm; (c) lightning occurs with a rapidly moving thunderstorm where rainfall does not have sufficient time to accumulate (Rorig and Ferguson, 1999, 2002).

Several fire weather indices have also been developed to guide forecasts for the potential of fire ignition and spread. The Haines Index, which is widely used in the United States, is an integer scale (1-6) that indicates the potential for fire ignition and growth based on two equally weighted ingredients for moisture and stability, respectively derived from the surface dew point depression and atmospheric lapse rate (Haines, 1988;
Unstable conditions in the lower troposphere commonly result in a greater chance for lightning strikes, higher smoke plumes, stronger entrainment of the air near the fires, and faster spread rate, all of which can lead to the “extreme fire behavior” syndrome (Werth and Ochoa, 1993).

In contrast to the Haines Index, the fire indices used in the Canadian boreal forest regions generally disregard atmospheric instability variables and put more focus on biomass moisture content. For example, the Canadian Fire Weather Index (FWI) is based on the use of surface temperature, relative humidity, rainfall, and wind speed to derive the amount of biomass moisture content used for assessing fire potential and spreading in the unique boreal ecosystem (Amiro et al., 2004). The same index is also used in Alaska to complement their own Alaska Fire Potential Index (FPI), which is an integer scale from 1 to 100 ranking the level of biomass moisture content for specific vegetation types based on the satellite derived Normalized Difference Vegetation Index (NDVI) along with other surface observations (Burgan et al., 1998).

While the key meteorological factors for fire ignition and spread are qualitatively known, their interplay, which results in lightening activity that ultimately ignites the fires, has not been quantitatively analyzed. This analysis is paramount to explaining the regional and interannual variability of wildfires in boreal North America. Even with instability recognized as a fundamental component of the Haines Index, there has never been an attempt to quantitatively assess the importance of this variable in fire ignition, especially over large temporal and spatial scales in the boreal forest. Furthermore, instability is paramount in determining the potential for convection and dry lightning
(Rorig and Ferguson, 1999, 2002); but little work has been done to investigate its relationship with dry lightning strikes and fire locations across boreal North America.

The lack of a study on possible relationships between low-level instability and other meteorology factors in the formation of lightning and fire ignition is partially due to the dearth of spatiotemporally collocated meteorological, lightning, and fire data. Often, scattered reports of weather, fire, and burned area from ground observations are used to characterize fire variability. Admittedly, these reports are not very reliable in describing the fire spatial distribution, temporal distribution (including the start and end dates), and intensity over the vast, sparsely populated boreal forests (Stocks et al., 2002; Flannigan and Wotton, 1991).

This study builds upon the following observational advancements to systematically investigate the cause of the variability in wildfire activity throughout boreal North America: (a) the development of ground-based lightning observation network with large spatial coverage in Alaska and Canada; (b) the high spatiotemporal meteorological reanalysis over North America; and (c) the near daily measurements of fire location and intensity with global coverage from NASA’s MODerate Resolution Imaging Spectroradiometer (MODIS). In addition to discerning fire locations with unprecedented accuracy (e.g. Justice et al., 2002), MODIS can measure fire radiative power (FRP), a parameter directly reflecting fire intensity and emission. This product, pioneered by MODIS, resulted in the first quantitative global survey of fire intensity (Ichoku et al., 2008a). By integrating data from (a)-(c) at relatively high spatiotemporal resolution in this paper, a detailed statistical analysis is conducted to understand the meteorological conditions necessary for dry and wet lightning events. The analysis
further quantifies the effect of lightning on boreal fire activity characterized by MODIS for the fire seasons of 2000-2006.
2. Data

2.1 MODIS Fire Products

The MODIS sensor, part of NASA’s Earth Observing System (EOS) and one of the five sensors aboard the polar-orbiting Terra satellite (launched 19 December 1999) provides all of the fire data used in this study including: the number, location, and intensity of fires across the globe. Specifically, this study uses the MODIS level 2, collection 4 fire product with a spatial resolution of 1 km at nadir (Giglio et al., 2003; Ichoku et al., 2008a). Terra MODIS has 36 spectral bands ranging from 0.4 – 14.2 µm with equator crossing times of 10:30 am and 10:30 pm local time (Kaufman et al., 2003). A second MODIS sensor was launched aboard the Aqua satellite on 4 May 2002 with equator crossing times of 1:30 pm and 1:30 am, providing full global coverage on a daily basis when combined with Terra (Kaufman et al., 2003). MODIS has a swath width of 2330 km and these swaths overlap poleward of 50° latitude, enabling either MODIS sensor to achieve complete daily daytime and nighttime coverage for these regions. Therefore, on average there are four possible fire observations per day globally when considering both MODIS sensors (e.g. Ichoku et al., 2008a). Since this study focuses on variability of fires in boreal North America (50–75°N), only the Terra fire data were used because it provides the longer data record (starting in 2000) of the two MODIS sensors.

When compared to earlier satellite sensors, MODIS is unparalleled in fire detection because of its ability to detect both low and high temperature fires as a result of synergy between its two 4 µm (more precisely 3.96 µm) channels whose dynamic ranges are complementary. The first 4 µm channel with a low signal-to-noise ratio saturates at
331 K brightness temperature, and thus serves as the primary channel for fire detection (Justice et al., 2002); the second channel saturates at 500K and is used to detect fires with brightness temperatures higher than 331 K (Justice et al., 2002). Other satellites with fire detection capabilities, such as the Advanced Very High Resolution Radiometer (AVHRR) and the Along Track Scanning Radiometer (ASTR), have much lower saturation brightness temperatures of about 325 K and 312 K respectively (e.g. Gao et al., 2007; Kelha et al., 2003) making it difficult to detect weak or intense fires.

The MODIS fire detection algorithms retrieve fire locations through a hybrid, contextual process beginning with the absolute detection of a fire pixel (Fig. 2). A set of thresholds for reflectance at 0.86 µm and brightness temperature (T) in the infrared channels (4 µm and 11 µm) are used to remove sun glint, cloudy pixels, and to immediately disqualify a pixel as a potential fire pixel (Justice et al., 2002; Giglio et al., 2003). The second step is relative fire detection, which relates the brightness temperature of the potential fire pixel with the surrounding background pixels and applies to all cloud-free and sun glint-free pixels regardless of their classification in the first step. Potential fire pixels are defined as those with $T_4 > 325$ K ($>310$ K) and $T_4-T_{11} > 20$ K ($>10$ K) for daytime (night) observations (Giglio et al., 2003). A 3x3 pixel square widens as necessary around a potential fire pixel until at least 25% of the pixels in the square are valid background pixels (absence of fire) and the number of these valid pixels is at least eight. If enough valid background pixels are obtained, the mean (M) and absolute deviation (S) of $T_4$, $T_{11}$, and $T_4-T_{11}$ are computed (Giglio et al., 2003). Finally, several tests including the absolute check in the first step and relative detection based on the
results of M and S are used to finally classify or disqualify a potential pixel as a fire pixel.

In addition to discerning fire location and brightness temperature, the MODIS fire algorithm also retrieves the fire radiative power (FRP) using only the 4 µm channels: (Kaufman et al., 1998a, 1998b):

$$FRP = 4.34 \times 10^ {-19} (T_4^8 - T_{4b}^8)$$

where $T_{4b}$ is the background temperature, yielding FRP in units of MW per pixel area (Kaufman et al., 1998a). It has been shown that the FRP can be used as a quantitative indicator for fire intensity and is proportional to both the fire’s fuel consumption and smoke emission rates (e.g. Wooster et al., 2002, 2003, 2005; Ichoku and Kaufman 2005; Roberts et al., 2005, 2008; Ichoku et al., 2008a, 2008b; Jordan et al., 2008). In contrast to earlier sensors, MODIS is currently the only operational satellite sensor designed to specifically measure FRP (e.g. Kaufman et al., 1998a, 1998b; Ichoku et al., 2008a). The higher saturation temperatures of MODIS allow for the derivation of FRP for nearly every fire it detects, although when $T_4 \gg 500$ K, the brightness temperature may be truncated, possibly leading to underestimation of FRP. However, such saturated cases seldom occur (e.g. Ichoku et al., 2008a).

The major caveats of the MODIS fire products in the boreal regions are sun glint, coastal false alarms (water reflectance), and clouds that may hamper the fire detection. The algorithm can account for these non-idealities by applying water masks and cloud masks, although these filtering processes are not perfect (Kaufman et al., 1998a; Giglio et al., 2003). Validation studies showed that the probability of fire detection by the collection 4 algorithm in the boreal forest is ~80-100% during the day and near 100% at night (Giglio et al., 2003). The smallest detectable fire size in any given pixel was found
to be ~100 m² (Giglio et al., 2003). Though hard to validate directly, MODIS FRP was found to be in good agreement with several early validation studies (Wooster et al., 2003; Roberts et al., 2005; Ichoku et al., 2008a).

### 2.2 Meteorological Data

Meteorological data are obtained from the North American Regional Reanalysis (NARR) data archived at the National Climatic Data Center (NCDC). Through data assimilation, the NARR blends a variety of observational data into Eta model output containing 45 layers in a vertical mesh across the North American continent with ~32 km grid spacing. The NARR output is produced every 3 hours daily starting from 1979 (Mesinger, 2006). At a much higher resolution than the global reanalysis (typically at 100-200 km), the NARR provides a more detailed reanalysis of meteorological and surface variables (Ebisuzaki, 2004). A collection of NARR monthly means and 3-hourly data for several NARR variables including soil and atmospheric moisture, instability, precipitation, etc. are used in this study (Table 1). To address the role of low-level instability, the surface-based convective available potential energy (CAPE) is used. Commonly included in convective forecasts, CAPE is directly related to the maximum potential vertical speed within an updraft; therefore, higher values indicate a greater potential for convection (thunderstorms).

### 2.3 Lightning Data

Lightning data are obtained from the Canadian Lightning Detection Network (CLDN) owned by Environment Canada and the Bureau of Land Management’s Alaska Lightning Detection Network (ALDN). The data include the location, peak current, polarity, and multiplicity of an individual lightning strike (e.g. Reap, 1991; Cummins et
al., 1998; Burrows et al., 2002). For the purposes of this paper, cloud-to-cloud discharges are ignored and only cloud-to-ground (CG) discharges are considered. CG lightning commonly consists of several separate strokes forming the individual flash (multiplicity). However, in this study, each large lightning flash is considered as a single strike regardless of the multiplicity.

There are two types of sensors used to detect lightning across the North American Continent: Lightning Positioning and Tracking Sensors (LPATS) and Improved Performance Combined Technology sensors (IMPACT). LPATS uses the time-of-arrival method to detect lightning while the IMPACT sensors use both time-of-arrival and direction finding (Cummins et al., 1998; Burrows et al., 2002). The time-of-arrival method is based on the electromagnetic field released by a CG lightning flash at about 1 kHz to 1 MHz (Cummins et al., 1998). These radio signals travel at close to the speed of light and at least two sensors are used to define separate hyperbolas based on the time-of-arrival of the radio waves at each sensor. The intersection point of the separate time-of-arrival hyperbolas is the location of the CG flash and therefore, a higher number of sensors detecting a flash will result in a higher accuracy in the location of the flash (Cummins et al., 1998). The IMPACT sensors combine this technology with direction finding which uses triangulation of the magnetic direction vectors (based on the CG electromagnetic field) at several stations to determine the location of a CG flash (Reap, 1991; Cummins et al., 1998).

The CLDN uses 82 total sensors across the country (about 34 in the study region) for lightning detection (Fig. 3) and most are LPATS-IV with the recent inclusion of several IMPACT sensors (Burrows et al., 2002). The ALDN uses 9 IMPACT sensors
(upgraded in 2000) concentrated in the center of Alaska (Fig. 3) where the majority of lightning events are known to occur (Dissing and Verbyla, 2003). The combination of these sensors provides spatial coverage for the majority, if not all, relevant regions used in this study. Furthermore, the detection efficiency of CG lightning in the CLDN (ALDN) is roughly 85-90% (80%) with a positional accuracy of 500 m (1 km) or better (Burrows et al., 2002; Dissing and Verbyla, 2003). It is important to note that the ALDN was upgraded to IMPACT sensors in 2000 and that should result in higher spatial and temporal detection efficiencies since that time.
3. Methodology

3.1 Data Integration

In order to facilitate our analysis, the MODIS fire data and the lightning data points are geographically matched into the mesh of NARR grid boxes. The matching algorithm computes the distance between each data point and the center of a grid box using spherical coordinates, and accounts for the variation (5–8 km) of the NARR’s grid size (~32 km in average) in the Lambert Conformal Conic projection. The number of lightning strikes and fire counts in each NARR grid box are respectively summed for each day essentially creating two additional NARR variables representing the daily occurrence of fire and lightning. Hence, the matching algorithm generates an integrated, gridded dataset that includes the means of each meteorological variable (derived from the 3-hourly NARR data), the total number of lightning strikes, and the Terra MODIS fire counts at each NARR grid box for each day.

Several new variables important for discerning atmospheric regimes for igniting fires are derived from the integrated dataset at each NARR grid box including: the number of dry and wet days, the number of dry and wet lightning strikes, and the daily maximum temperature (Table 1). Dry (wet) days are simply a running total of days for each NARR grid box where less than 2 mm (≥ 2 mm) of precipitation is observed during the 24-hour period. The dry (wet) day variable is set to zero when a grid box receives a precipitation amount ≥ 2 mm (< 2 mm). Similarly, dry (wet) lightning strikes are defined as any strike occurring in a NARR grid box that receives less than 2 mm (≥ 2 mm) of precipitation for each daily time step. The 2 mm definition used here is similar to that
used in Hall (2007) and less than the 2.54 mm definition used in Rorig and Ferguson (1999, 2001). In contrast to earlier studies of dry lightning activity using precipitation data from scattered surface observations, this study allows for a unique, high-resolution dataset of dry lightning activity across the entirety of northern North America regardless of population and instrument placement.

3.2 Regions of Study

The procedure used to examine wildfire variability across the North American boreal forest consists of two steps: (1) a general large spatial and temporal analysis to discern the most likely variables contributing to wildfire variability and (2) a statistical analysis at fine temporal and spatial scales to quantify the interplay of the predetermined variables of interest using several small focus regions across the boreal forest. For step 1, boreal North America is subdivided into two regions: Alaska and a portion of Canada west of the Great Lakes and Hudson Bay (Fig. 4 regions A and B). The boundaries of these regions follow the boundaries defined in Ichoku et al. (2008a) as part of a global study on wildfire patterns and intensity where 36 sub-regions were used and each region was created such that it contained a dominant ecosystem type. In this case, regions A and B have the boreal forest as the main ecosystem type and the actual boundaries, boxed area, and total NARR grid boxes for these regions are found in Table 2.

The Canada Region (B) is sparsely populated with the majority of the population located in the southern third of the region near the cities of Edmonton (53.5N, -113.5W) and Calgary (51.0N, -114.1W). The Alaska region (A) is even less densely populated with most of the population located near the cities of Fairbanks (64.8N, -147.7W) and Anchorage (61.2N, -149.9W). Furthermore, previous work has highlighted the
importance of lightning strikes over human involvement in fire ignition across the major boreal regions (Stocks et al., 2002; Boles and Verbyla, 2000). Therefore, the lack of population, especially in the core of the boreal forest, coupled with the results from earlier studies on fire activity allows for the assumption that any anthropogenic influence is minimal in the study regions.

Consequently, the analysis in step 2 focuses on 6 smaller regions (Table 2, regions 1-6) in both Alaska and Canada (Fig. 4, regions 1-6). While it is nearly impossible for each region to contain exactly the same type of forest vegetation, these small regions were defined such that they contain only the core of the dense boreal forest. The actual analysis combines regions 1-3 (western domain) and regions 4-6 (eastern domain) to create two datasets specifically for the North American boreal forest belt. The eastern domain includes the portion of Canada known to have the highest frequency of fires; where up to 0.74% of the land area burns annually with low human impact (Stocks et al., 2002; Skinner et al., 2002). Similarly, the western domain covers nearly all of the Alaskan boreal forest. In addition, the western domain is located in the mountainous boreal forest and eastern domain is located in the relatively flat boreal forest in Canada. This spatial orientation allows for a comparison between eastern and western locations as well as high and low elevation locations. These boreal study domains, located within the larger regions (A and B) defined in step 1, allow for a detailed spatial and temporal analysis of the meteorological variables of interest found in step 1.

3.3 Analysis Procedure

In the high latitudes, the fire season (when the vast majority of fires occur) is limited by the duration of a short warm season and is defined as June-August in this study
(e.g. Skinner et al., 1999; Stocks et al., 2002; Fauria and Johnson, 2006). Based on the predefined length of the fire season, step 1 in the analysis investigates the interannual variability of fire activity in each large regional domain (A and B) to provide a general representation of the meteorological factors responsible for active fire years. This is accomplished using the monthly area average of each NARR variable, lightning data, and the MODIS fire data. Each domain is analyzed comparatively and independently for a wide array of fire related meteorological variables. Correlation coefficients between the fire, lightning, and meteorological data are computed for each region (A and B) to ascertain the general meteorological conditions necessary for active fire seasons in each region.

Based on the results obtained at the large spatial and temporal scale (step 1), a detailed analysis (step 2) using samplings at a finer temporal (daily) and spatial scale (native NARR grid of 32 km) is then performed using the gridded daily data for the six small regions comprising the eastern and western study domains. The goal in step 2 is to discern the major contributing variables to the number of observed fires in each sub-region (eastern and western domain) with an emphasis on lightning activity, the major source of fire ignition in boreal North America (Stocks et al., 2002; Boles and Verbyla, 2000). This analysis includes several key factors: (1) the probability of dry and wet lightning occurrence as a function of the contributing meteorological variables found in step 1, (2) the meteorological influences on lightning-related fire activity, (3) the lag-effect (holdover-effect) following a lightning strike that ignites a fire, and (4) a comparative analysis between the eastern and western domains to understand any regionally important factors (such as topography) for lightning and fires. The specific
techniques used to investigate these factors are explained in the following sections.
4. Results and Discussion

4.1 Large-Scale Analysis

The preliminary analysis step begins by computing the seasonal Pearson correlation coefficients (R) between the fire, lightning, and meteorological data for region A and region B using each analysis variable found in Table 1 to discern the interannual variability of the boreal fire seasons. Following this analysis, only a few key meteorological variables stand out. As expected, the 500 hPa geopotential height displays a positive relationship with both the number of fire counts and FRP Flux in each region with $R = 0.83$ ($R = 0.55$) in region A (region B) for fire count data (Table 3). These results highlight the influence of the large-scale pattern described in earlier studies (e.g. Skinner et al., 1999, 2002; Fauria and Johnson, 2006) where anomalously high 500 hPa heights are found to set the stage for active fire weather periods.

4.1.1 Instability and Lightning

While examining correlations of fire counts (number of fire pixels) against the meteorological parameters affected by the large-scale pattern, three parameters (the surface-based CAPE used as a measure of instability and potential for convective activity, total cloud-to-ground lightning strikes, and total dry lightning strikes) are immediately evident as an important variables in region A with $R = 0.97$, $R = 0.93$, and $R=0.73$, respectively. Similar results are obtained when using the FRP flux, defined as the total FRP divided by the total land area within the regional domain (Table 3). These
results suggest that changes in instability and lightning activity associated with the large-scale pattern influence both the number and the intensity of fires in region A (Alaska).

Conversely, results from region B (Canada) show a relatively strong negative relationship between the fire data, instability (CAPE), and lightning activity with R = -0.67, and -0.53 respectively for fire count data. After close scrutiny, the unexpected results in region B are likely due to the height gradient between a ridge and a trough at 500 hPa bisecting this region in the seasonal mean with a ridge present in the west and trough in the east (contours in Fig. 4). This pattern creates a highly variable environment with respect to geopotential height just east of the Canadian Rockies that does not allow a specific synoptic pattern to remain in place for long temporal durations (Skinner et al., 2002). To investigate this discrepancy, plots of surface CAPE and total lightning strike anomalies are produced for each fire season (2000-2006). As an example, the fire season of 2006 conforms to the expectation that the spatial distribution of anomalously high CAPE and lightning strikes will coincide with the highest concentration of fire counts and high FRP values (> 1000 MW) (Fig. 5). This particular fire season also follows a traditional synoptic setup (Fig. 1) for an active fire year in central Canada (Skinner et al., 2002).

The fire season of 2004 is the most active fire season of the seven-year study interval in both region A and region B (Fig. 5). This particular fire season is a classic example of an active western boreal fire year (Skinner et al., 2002) with Alaska and the extreme western portions of Canada experiencing prolific fire and lightning activity under a positive height anomaly. However, from this example, it becomes obvious that
there is an unconformity in central Canada immediately east of the Rocky Mountains. Previous studies have shown similar examples where a certain amount of fire activity occurs within the trough in the seasonal 500 hPa height mean (e.g. Skinner et al., 2002) suggesting that the 500 hPa height is not a perfect tool for assessing fire variability under certain synoptic environments in every region of the boreal forest. Therefore, it is also obvious that discrepancies may exist between the meteorological setups producing the dry lightning events that ultimately ignite fires across the boreal forest.

4.1.2 Moisture Variables

As expected, both relative humidity (RH) and fire season precipitation show a negative correlation with the fire data in region (A). However, the weakness of this negative correlation (e.g. $R_{\text{fire count}} = -0.42$ and $R_{\text{FRP}} = -0.40$) is a surprise because moisture is generally considered as a key component in many of the fire weather indices such as the FPI and FWI used in boreal North America. In region B, the influence from RH and fire season precipitation is even less with RH displaying a weak positive correlation. While necessary for short-term forecasts of fire potential and behavior, these variables do not seem to be major factors affecting the fire season variability in the boreal regions.

In contrast, the derived consecutive dry days variable does show a relatively strong, positive correlation with fire counts and FRP flux in both regions with $R_{\text{fire count}} = 0.63$ and $R_{\text{FRP}} = 0.57$ ($R_{\text{fire count}} = 0.61$ and $R_{\text{FRP}} = 0.70$) in region A (region B). This result quantitatively supports the hypothesis made in earlier studies, with limited ground-based data (e.g. Flannigan and Harrington, 1988), that the role of the duration of dry conditions is far more dominant than the total precipitation in regulating the variation of
fire activity. One likely explanation of this counter-intuitive result is that a fire season with ample precipitation may still be active if there is a long stretch of dry conditions between wet periods. Furthermore, the upper layer of soil and plant debris would be greatly affected by a long stretch of dry days, and the moisture at this particular layer is indeed the major moisture parameter considered in the Canadian Fire Weather Index (Amiro et al., 2004).

When investigating the average FRP of each individual fire, only the precipitation prior to the start of the fire season (November-May) stands out with $R = -0.71$ in region A. The pre-season precipitation variable is also important to fire season variability in region B with $R = -0.79$. Following a dry winter and/or spring, forest vegetation, especially smaller undergrowth, will not grow as healthy, which allows for more dead plant material during the fire season to provide a greater quantity of available fuel. This additional fuel can result in fires that burn hotter and/or grow larger thereby increasing the FRP especially if conditions become anomalously dry during the fire season.

### 4.2 Focused Sub-Regional Analysis

While the large-scale analysis (regions A and B) in the previous section is helpful toward a general understanding of the effects of the synoptic pattern on fire activity, a finer spatial and temporal analysis is necessary for understanding the meteorological factors favorable to cause the lightning and ultimately, the fires. Therefore, the secondary analysis step is initiated using the eastern and western boreal domains derived from sub-regions 1-6. This analysis incorporates the daily gridded dataset, thereby allowing for a wide array of data points (> 700,000 when including both domains) rather than a regional mean. Based upon the large-scale analysis, it becomes clear that certain
meteorological variables, particularly lightning, may influence the number of observed fires but not necessarily the FRP. With lightning activity recognized as the major cause of boreal fire ignition, the fine-scale analysis herein focuses mainly on its relationship with fire counts (number of fire pixels) and other meteorological variables. Detailed analysis of meteorological variables and their effects on FRP will be left for a future study.

4.2.1 Boreal Lightning Activity

4.2.1a Lightning Statistics

From a spatial perspective, the total number of lightning strikes per grid box observed during the 7-year study interval increases from the coast to the interior regions of Canada and Alaska especially in the southern portions of the boreal forest. The eastern domain experiences much more lightning activity (often 2000-6000 strikes per grid box) than the western domain (often 500-2000 strikes per grid box). However, the western domain does coincide with a local maximum of lightning activity in interior Alaska and Canada (Fig. 6a). In terms of fire counts, however, the pattern is opposite. Namely, the majority of grid boxes in the western domain experience ~400-500 fire counts during the same seven-year time period while only a few grid boxes in the eastern domain approach 300 fire counts (Fig. 6b). It should be noted that this discrepancy only reflects the seven years of data in this study and is not necessarily representative at climatic time scales.

Even though previous studies qualitatively suggest that lightning may ignite the majority of fires in the North American boreal forest (Boles and Verbyla, 2000; Stocks et al. 2002), results here indicate that dry strikes are only a small portion of all lightning activity in these regions. In the western (eastern) domain, only 23% (21%) of lightning
strikes are dry when considering all grid boxes in the domain. From a monthly perspective, 27-31% (23-24%) of lightning strikes are dry in June and August while only 17% (18%) are dry in July for the western (eastern) domain. The interannual variability of dry lightning activity ranges from a minimum of 17% (13%) to a maximum of 35% (26%) during the 7-year study period in the western (eastern) domain. Surprisingly, the highest percentages of dry lightning activity do not correspond to the most active fire seasons when investigating the eastern and western domain as a whole.

In contrast to the total number of lightning strikes (Fig. 6a), the mountainous regions in Alaska and western Canada (western domain) contain the highest percentage of lightning strikes occurring as dry strikes with several individual grid boxes greater than 80% (Fig. 6c). These localized values are much higher than the percentage of dry strikes in the western domain as a whole (23%) because there are still many grid boxes with less than 40% dry strike activity. Therefore, localized influences, such as topography, likely affect the distribution between high percentage and low percentage dry strike grid boxes. Previous work has shown a positive relationship between total lightning strikes and elevation (Reap, 1991; Dissing and Verbyla, 2003), but the effect of topography on only dry strikes is still unclear. Regardless of potential topographical influences, the western and eastern boreal domains contain a greater quantity of grid boxes with a high percentage of dry strikes than non-forested locations to the south. Furthermore, the individual grid boxes (within the eastern and western domains) with a high percentage of dry strike activity commonly experience a greater number of fire counts over the seven-year study interval.
4.2.1b Meteorological Factors Associated with Lightning Activity

Similar to the large-scale analysis, CAPE and the 500 hPa geopotential height stand out in the fine-scale analysis while examining the variation of total fire counts in the western and eastern domains. One explanation is because these variables are directly related to the potential for dry lightning, the presumable cause of many boreal fires. To examine the effect of these variables on all lightning activity (including wet events), the probability of dry and wet strikes occurring in each grid box is computed for all observed values of CAPE and 500 hPa geopotential height in both the eastern and western domain for 2000-2006. To begin, the range of the observed 500 hPa height and CAPE data is divided into several bins (~20 bins per variable). The available data points (~ 400,000), derived from each grid box over the seven-year interval, are then sorted into their respective bins (based on 500 hPa height and CAPE) and summed ($D_{\text{total}}$) allowing for the visualization of the data distribution. Similarly, this procedure is applied to only data points with dry or wet lightning occurrence ($L_{\text{total}}$). Next, the individual dry or wet lightning strikes occurring within the grid boxes of $L_{\text{total}}$ are also summed ($S_{\text{total}}$). This allows the average number of dry or wet lightning strikes occurring in a given grid box ($S_{\text{avg}}$) to be computed for each bin: $S_{\text{avg}} = \frac{S_{\text{total}}}{L_{\text{total}}}$. Finally, the probability (Pr) of dry or wet lightning occurrence is computed for each bin: $Pr = \frac{L_{\text{total}}}{D_{\text{total}}}$. 

The distribution of data points the eastern domain (Fig. 7) covers a much larger range of CAPE values (0-3000 Jkg$^{-1}$) than the western domain (0-1400 Jkg$^{-1}$). Reflecting the many days lacking convective activity, the majority of data points are associated with
relatively low CAPE values of less than 200 Jkg\(^{-1}\) (700 Jkg\(^{-1}\)) in the western (eastern) domain. The influence of latitudinal location is also evident with a shift toward slightly higher 500 hPa heights in the eastern domain. When considering the largest quantity of individual dry and wet lightning strikes per grid box, the representative CAPE values become 500 Jkg\(^{-1}\) (1000 Jkg\(^{-1}\)) in the western (eastern) domain (Fig. 8). The corresponding levels of 500 hPa height are 5600 meters and 5700 meters in the western domain and eastern domain, respectively.

In the eastern domain, the highest probability (> 50%) of dry lightning activity is associated with CAPE values greater than 1500 Jkg\(^{-1}\) and 500 hPa geopotential heights greater than about 5700 meters (Fig. 9). In contrast, a high probability for dry lightning in the western domain is observed with much lower levels of CAPE and 500 hPa geopotential heights with minimum values of 300 Jkg\(^{-1}\) and 5450 meters, respectively. The lower values are likely a result of the higher latitudinal location and topographic effects that may allow for localized convergence and enhanced updrafts that would otherwise not produce a thunderstorm. However, even with latitudinal and possible topographic influences, the highest probability of dry strike occurrence in both domains is only found near the maximum observed range of CAPE values for each corresponding level of 500 hPa geopotential height (grey shading in Fig. 9). Furthermore, the isolated nature of many dry thunderstorm events highlights the potential for a strong capping inversion that must be overcome with only a few updrafts growing strong enough to become a thunderstorm (Flannigan and Wotton, 1991; Rorig and Ferguson, 1999; Hall, 2007). This explains why the highest potential for dry thunderstorm activity is associated with the most extreme values of low-level instability. Therefore, the knowledge of
representative CAPE values for each 500 hPa height level in each domain, as shown in Figure 9, can aid in forecasting these events.

While there are distinct limits on CAPE and 500 hPa height for dry lightning strikes, wet lightning strikes are common in a variety of synoptic and thermodynamic environments in both domains. For example, wet strikes do occur with similar CAPE and 500 hPa height values as dry strikes. However, high probabilities of wet lightning also exist with much lower instability and heights. This large range is likely a result of many wet events occurring along frontal boundaries where 500 hPa heights are lower thus reducing the maximum observed levels of CAPE. Many of these events are also associated with large convective complexes rather than isolated thunderstorm activity thereby, reducing the chance of fire ignition (Flannigan and Wotton, 1991).

4.2.2 Combined Analysis: Lightning Activity and Fire Ignition

With an understanding of the conditions associated with dry lightning activity, the next step scrutinizes the conditions necessary for dry lightning strikes to actually result in a fire. In the western domain, seasonal total fire counts range from less than 10 to as many as 34,000 in the extreme fire season of 2004 and seasonal total dry lightning strikes range from 4000 to 23,000. In the eastern domain, total dry lightning strikes range from 40,000 to over 100,000 although the total fire counts only range from 5 to 5100. Furthermore, the correlation between fire counts and lightning activity for each domain is not the same. To investigate these discrepancies, the fire season (92 days) is divided into a series of temporal segments with an equal length of days for each year. The correlation coefficients between fire counts and dry, wet, and total lightning strikes are then computed for each individual temporal segment in both the eastern and western domains.
(Figs. 10a,b). It is expected that such a correlation should increase as the length of the segment reaches the total days for the season and hence, many localized (and somewhat random) processes will be averaged out to allow the dominant mechanisms for the interannual variability to stand out.

The western domain follows the expected result nicely with R-values increasing from 0.20 at segment length of 9 days to 0.80 at the seasonal cutoff (Fig. 10a). However, the eastern domain deviates from the expectation after the 15-day division with R approaching -0.60 by the seasonal cutoff (Fig. 10b). This result is likely related to the mechanisms responsible for lightning activity in each domain. In the western domain, prolific lightning activity only occurs in active fire years because this is when the large-scale pattern becomes conducive to enhanced thunderstorm development in these high latitudes by allowing low-level instability (CAPE) to increase dramatically (Skinner et al., 1999; Dissing and Verbyla, 2003). Furthermore, the synoptic pattern displays limited fire season variability in the region encompassing the western domain (Skinner et al., 2002), suggesting that a fire-conducive pattern will remain in place for relatively long durations.

In contrast, the eastern domain, located at lower latitudes, experiences a great deal of lightning activity in every season in association with both unstable air mass events and large frontal disturbances. During an active fire season, the frequency of large frontal disturbances decreases due to an increased presence of positive 500 hPa height anomalies (Skinner et al., 1999, 2002) and isolated, instability driven thunderstorms likely dominate. Therefore, the total number of lightning strikes and low-level moisture availability decreases but the number of fires (ignited by lightning) subsequently
increases. As observed in the large-scale analysis and previous studies (e.g. Skinner et al., 2002), the eastern domain is located in a highly transient synoptic environment allowing for more monthly variations than the western domain. Therefore, many fire-conducive patterns will remain in place for only a few days to a few weeks helping to explain the negative correlation after the 15-day division. This analysis builds on the large-scale results (region B) and shows that there are many complexities with lightning activity and fire ignition in the smaller eastern domain. It is very likely that a fire will be ignited during short-lived, but favorable, dry lightning conditions and will burn during the days following the synoptic pattern change. Therefore, it is also possible that some of these lightning-caused fires will be extinguished when the pattern shifts and less favorable burning conditions exist.

4.2.2a Holdover Fires

In order to address the specific role of lightning in fire ignition, the lag between the actual strike and the fire start must be accounted for. This lag effect results from the time it takes for a fire, which may smolder for several days (holdover fire), to become substantial enough to be observed by either satellite or ground observations following the strike. It has been suggested that these holdover fires can take as long as 7-10 days to become visible when using surface observation techniques in the remote boreal forest (Flannigan and Wotton, 1991). When using MODIS data, this time should be reduced but it will not be completely removed due to cloud cover delays. In the western (eastern) domain the average number of fires per dry strike is about 0.50 (0.04) and 0.15 (< 0.01) for wet strikes without accounting for the holdover effect. The lower values in the eastern domain are related to the mechanisms described in the previous section.
To address the actual holdover effect, the efficiency of dry and wet lightning strikes in producing fires, (defined as the number of fire counts divided by the number of dry or wet lightning strikes) is computed for each grid box over the seven-year interval in the western domain and eastern domain. Similarly, the likelihood of a fire occurring in a dry or wet lightning grid box is also computed through a “hits and misses” technique. This is accomplished by assigning a value of 1 to any data points with fires and lightning \( (L_1) \), assigning a value of 0 to data points with only lightning \( (L_0) \), and ignoring all data points with neither fires nor lightning. The probability (likelihood) of lightning to ignite a fire \( (Pr) \) is then computed for each grid box: 

\[
Pr = \frac{L_1 + L_0}{L_0 + L_1}.
\]

The average efficiency and likelihood for both the western and eastern domain is then calculated while lagging the fire data from 1-8 days and keeping the lightning data at a lag of zero (Figs. 11a,b). To account for possible on-going fires, these calculations were also performed by applying running means of 2-5 days to the fire data prior to the efficiency and likelihood lag calculations (not shown). However, any influence on efficiency or likelihood from this on-going fire effect was found to be negligible.

As expected, the efficiency of dry lightning and the likelihood of a fire occurring in a dry lightning grid box are higher than wet lightning in both domains. However, wet lightning still shows efficiency and likelihood values greater than zero suggesting that wet strikes, presumably associated with precipitation amounts just above 2 mm, may also play a role in fire ignition. This “wet” influence would be most common with lightning striking away from the main precipitation shield or with dying thunderstorms. Regardless of lag, the efficiency of dry strikes in the western domain is higher than the
eastern with values of about 4 and 2.5 fires per dry strike respectively. Therefore, the chance of a dry lightning strike igniting a fire in the western domain is a factor of ~1.5 higher than the eastern domain. Similarly, the likelihood of dry lightning igniting a fire is also higher in the western domain.

It was expected that the efficiency and likelihood lag plots would show a distinct peak at the optimal lag needed to account for the holdover effect. However, the likelihood analysis (Fig. 11b) does not show a trend based on lag in either domain. Therefore, the holdover effect is based solely on the efficiency profiles. For example, the eastern domain shows a distinct increasing trend in dry efficiency until lag 3 (Fig. 11a) suggesting that a lag of 3 days must be accounted for. In contrast, the dry efficiency profile for the western domain contains a lot of variation and does not show a specific trend based on lag. Therefore, a lag of 2 days seems sufficient to account for holdovers. This assumes that fires become detectable slightly faster in the western domain than the eastern domain, which could be related to the meteorological discrepancies affecting the plots in Figure 10.

4.2.2b Meteorological Influences on Lightning Related Fire Activity

After accounting for the holdover effect by using a 2 day averaging period in the western domain and a 3 day averaging period in the eastern domain, the meteorological conditions resulting in fire ignition based on dry or wet lightning strikes are investigated. Using a method similar to the lightning activity analysis (Fig. 9), the probability of lightning-ignited fires occurring in each grid box is computed for all observed values of CAPE and 500 hPa geopotential height in both the eastern and western domain for 2000-2006. However, the probability calculation in this case (Fig. 12a), uses the likelihood
(hits and misses) technique described the previous section for each bin. In this case CAPE also serves a secondary purpose by affecting the potential for fire ignition to be successful. Previous studies have highlighted the importance of unstable conditions to stronger entrainment of the air near the fires and faster spread rate (e.g. Werth and Ochoa, 1993).

As discovered in the lightning activity analysis (Fig. 9), the representative values for CAPE and the 500 hPa geopotential height necessary to produce dry lightning in the western domain are 300 Jkg\(^{-1}\) and 5450 meters respectively. However, the values corresponding to a high probability of fire ignition via dry lightning are about 300 Jkg\(^{-1}\) and 5700 meters respectively (Fig. 12a). Therefore, it seems the dry strikes occurring with 500 hPa heights below 5700 meters have a very low probability to produce fires in this region. Furthermore, CAPE values greater than 300 Jkg\(^{-1}\) and 500 hPa heights above 5700 meters result in a chance of fire ignition associated with dry lightning of 15% to more than 50%. While showing a similar trend, the same association of dry lightning with fire ignition in the eastern domain is not as strong with the maximum chance of fire ignition only reaching above 50% in a few bins. In this domain, CAPE values greater than 800 Jkg\(^{-1}\) and 500 hPa heights at or above 5600 meters provide the best chance of fire ignition from dry lightning. These values are lower than the CAPE threshold of 1500 Jkg\(^{-1}\) and the 500 hPa height threshold of 5700 meters determined earlier for a high probability of dry lightning activity (Fig. 9).

While only one dry strike is necessary to produce a fire, the number of dry strikes necessary for a high probability of fires per grid box is less certain. Another consideration is that dry lightning will not spark a fire unless the fuel is sufficiently dry
and previous studies have highlighted many variables and methods available to address this moisture dilemma. From the large-scale analysis used here, the number of consecutive dry days stands out as the moisture parameter commonly associated with a large number of fires. To address the role of moisture, the probability analysis is performed using the total number of consecutive dry days and the total number of dry lightning strikes in place of 500 hPa height and CAPE (Fig. 12b). In this case, the total number of grid boxes with fire occurrence ($F_{\text{total}}$) and the total number of available grid boxes ($D_{\text{total}}$) over the seven-year interval are used to compute the probability for each bin: $\Pr = \frac{F_{\text{total}}}{D_{\text{total}}}$. In both the eastern domain and western domain, the probability of fire ignition within a grid box is highest after 10-15 consecutive dry days and 10-15 dry lightning strikes; this probability approaches ~50% after more than 20 dry days and/or more than 20 dry strikes. It seems that 10 consecutive dry days is an important consideration for fire potential. If there has been less than 10 consecutive dry days, the probability of a fire occurring in a given grid box is very low in both domains. Therefore, the consecutive dry days variable may be a better indicator of fire variability than 500 hPa heights in the transient eastern domain.

4.3 Discussion

While a detailed lag-analysis was conducted to account for holdover fires, the exact time of a fire start remains a mystery even with daily satellite observations in clear conditions, not to mention in cloudy conditions. If meteorological data with a smaller grid size becomes available, it is possible that even this resolution will be too coarse to capture exact meteorological factors for isolated lightning events and to establish cause
vs. effect. There is also a chance, although small, that fires may propagate from one model grid box to another. Due to the fact that precise scenarios for each individual fire are difficult to obtain, our results are statistical in nature, as shown here, by analyzing the large dataset to discern dominant mechanisms. In the next decade or two, spatiotemporally collocated half-hourly fire and lightning data obtained from geostationary satellite observations (such as from GOES-R) could provide valuable constraints in analyzing the timing and localized mechanisms for lightning-induced fires.
5. Summary and Conclusions

This study has provided a quantitative assessment of the meteorological environment behind lightning development and its influence on fire variability as observed by MODIS in the boreal forest of North America using an integrated approach with gridded datasets. Emphasis is on the understanding of meteorological factors such as CAPE and 500 hPa heights favorable for wet and dry lightning to cause fires, although several other fire-related meteorological variables (including: number of dry days, relative humidity, and pre-fire-season precipitation) are also analyzed in varying detail. The primary step to understanding fire variability begins with the analysis of conditions necessary for dry lightning to occur and the spatial distribution of dry lightning activity across the North American boreal forest belt. While dry lightning is paramount, the results here suggest that wet strikes have an impact, though minor, on fire ignition as well.

Atmospheric instability (CAPE), lightning strikes, and positive anomalies in the 500 hPa geopotential height field were found to explain more than 60% of the interannual variability in the number of fire counts in Alaska (A) while meteorological influences in the large Canada region (B) are very complex, especially east of the Canadian Rockies. At smaller spatial scales, there are clear differences in lightning activity between the mountainous western and the relatively flat eastern boreal forest study domains. For example, there is a greater chance of a lightning strike occurring as a dry strike and a higher chance that the strike will result in a fire for any given grid box in the western domain. Even though the eastern domain experiences many more lightning strikes per
grid box than the western domain, the mechanisms behind lightning occurrence are
different, with the western (eastern) domain showing a positive (negative) correlation
between fires and lightning strikes. Furthermore, the efficiency of dry strikes in
producing fires is nearly 50% lower in the eastern domain. Differences also exist when
investigating the number of fires per season in each domain (assuming variations in area
are negligible), with the western domain experiencing over 30,000 fire counts in active
seasons, while the eastern domain only reaches 5100 during the seven-year study period.

Deviations in the synoptic pattern (500 hPa heights) and low-level instability
(CAPE) stand out as key components to lightning variability in these regions which
influences wildfire ignition and variability. In the western domain, a 15% to more than
50% chance of a fire being ignited by dry lightning exists for CAPE values greater than
300 Jkg$^{-1}$ and 500 hPa heights above 5700 meters. In the eastern domain, the CAPE
threshold changes to 800 Jkg$^{-1}$ and the 500 hPa height threshold actually decreases to
5600 meters. The maximum chance of fire ignition is also weaker reflecting the low
efficiency values calculated for the eastern domain. Reasons for this discrepancy are
currently unclear, but an explanation may come from the differences in overall
meteorological pattern and/or the biomass itself in this domain. Regardless of location,
dry lightning strikes only occur near the maximum observed levels of CAPE for any
given value of 500 hPa height. Therefore, as recognized in the Haines index (Haines,
1988), low-level instability is a key factor in fire ignition in the boreal forest.

Following an investigation of many moisture variables and parameters used in fire
forecasts across the boreal forest, only the derived number of consecutive dry days stood
out when investigating the total number of fires. After 10 dry days occur for any given
grid box in either domain, the chance for a fire occurrence greatly increases and can reach more than 50% after 20 dry days. Similarly, the probability of fire occurrence is low with less than 10 dry lightning strikes per grid box but approaches values of 30-50% as the number of dry strikes per grid box increases. Therefore, in any region of the boreal forest, after a long duration of dry weather, relatively sparse dry lightning activity can easily result in fire ignition, but if the number of dry days is low, a greater number of dry strikes per grid box is required to produce a similar chance for a fire ignition.

Furthermore, consecutive dry days may be a better measure of fire season variability than 500 hPa heights in the eastern boreal forest because the total number of dry days is not necessarily affected by changes in the synoptic pattern (e.g. dry frontal passages).

If the data integration algorithm used in this study can be implemented in near real-time, dry lightning activity can be accounted for in fire weather forecasts, and the probability of a fire developing in the following days can be better estimated. Furthermore, with climate change becoming a major issue, it is easy to see that increased low-level instability brought on by warmer temperatures can result in an enhanced potential for lightning activity and a greater chance for fire ignition. Future work will focus on the FRP product provided by MODIS and will highlight the variables responsible for changes in the post-ignition fire intensity across the boreal forest. This analysis will inevitably incorporate ground-based observations to compare with the MODIS data. In addition, the charge and peak current of each wet or dry lightning strike could be investigated to discern their effects on fire ignition.
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References


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## Tables

### Table 1. Analysis Variables

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<thead>
<tr>
<th>NARR Meteorological Variables</th>
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<tr>
<td>1 Convective Precipitation</td>
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<td>2 Horizontal Moisture Divergence</td>
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<td>4 November-May Snowfall</td>
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<td>5 Fire Season Precipitation</td>
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<td>8 Soil Moisture (0-200cm)</td>
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Table 2. Specifics of the study regions displayed as red or black boxes in Fig. 4.

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Table 3. Correlations for selected meteorological variables, fire counts, and FRP data

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<th>Region B. (CANADA)</th>
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<td>Nov-May Precipitation</td>
<td>-0.05</td>
<td>-0.12</td>
</tr>
<tr>
<td>Total Dry Days per Grid Box</td>
<td>0.63</td>
<td>0.57</td>
</tr>
<tr>
<td>Relative Humidity (sfc)</td>
<td>-0.42</td>
<td>-0.40</td>
</tr>
<tr>
<td>CAPE</td>
<td><strong>0.97</strong></td>
<td><strong>0.96</strong></td>
</tr>
<tr>
<td>500 hPa Height</td>
<td><strong>0.83</strong></td>
<td><strong>0.83</strong></td>
</tr>
</tbody>
</table>

**|R| ≥ 0.70**: 90% significant **95% significant**

1. Correlation coefficient is computed from the seasonal averages of each variable.
Figures

Fig. 1. Example of two synoptic patterns associated with large area burned in Canada including the locations of the large fires (symbols on map) and estimates of area burned for each boreal ecosystem (Skinner et al., 2002). Solid lines are average actual heights ( contour interval 2 dams) and dashed lines are average anomalous heights (contour interval 10 dams, zero interval is bold).
Fig. 2. Flowchart containing the major steps within the Terra MODIS fire detection algorithm (Giglio et al., 2003).
Fig. 3. (Top) Locations of lightning detection sensors in Alaska (Dissing and Verbyla, 2003). (Bottom) Locations of lightning detection sensors in western Canada (Burrows et al., 2002).
Fig. 4. Global MODIS derived ecosystem map. Red boxes delineate the large study regions for Alaska (A) and Canada (B). The black boxes delineate the small boreal focus regions (1-6) defined for analysis in this study and the combination of regions 1-3 (4-6) is the western (eastern) domain. Dark green shading indicates the dense evergreen needle leaf forest common in boreal regions, tan shading is open tundra shrub-land, yellow is croplands, and orange is grassland. The white contours indicate the mean 500 hPa geopotential height field for the fire season (June-August) for the years 2000-2006.
Fig. 5. (Left) Surface CAPE anomaly in percent (color filled) and MODIS fire data for the fire seasons of 2004 and 2006. The MODIS fire pixels are denoted as grey dots except those with FRP > 1000 MW which are highlighted as black triangles. (Right) Positive and negative anomalies for total lightning strikes during the fire season. All anomalies are based on the 7-year (2000-2006) study interval, and the regional study domains for Alaska and Canada (A and B) are highlighted with grey boxes.
Fig. 6. (a) Total lightning strikes per grid box for the fire seasons of 2000-2006. (b) Total fire counts per grid box for the fire seasons of 2000-2006. (c) The percentage of lightning strikes occurring as dry strikes per grid box for the fire seasons of 2000-2006. The six boreal focus regions composing the western and eastern domains are displayed in black. White color indicates locations with no data.
Fig. 7. Distribution of the available data points as a function of CAPE and the 500 hPa geopotential height for the western domain (a) and the eastern domain (b). White areas do not contain observed data.
Fig. 8. The average number of lightning strikes (dry and wet) per grid box as a function of CAPE and 500 hPa geopotential heights for the western domain (left) and the eastern domain (right). White areas do not contain observed data and the values of the western domain color bar are 1/5 of the values in the eastern domain color bar.
Fig. 9. Averaged probability of lightning activity (dry or wet) occurring within a grid box as a function of CAPE and 500 hPa geopotential heights for the western domain (left) and the eastern domain (right). The observed CAPE and height values for 2000-2006 with a probability of dry lightning occurrence ≥ 25% are shaded in color, values with a probability of dry lightning occurrence between 0 and 25% are shaded in black, values without lightning occurrence are shaded in grey, and white areas do not contain observed data.
Fig. 10. Correlation coefficients between fire counts and total, wet, and dry lightning strikes for 6 temporal divisions ranging from 3 to 92 days in the western domain (a) and the eastern domain (b). The fire season total is 92 days for June-August.
Fig. 11. (a) Efficiency of dry and wet lightning strikes in fire ignition for the western domain (left) and the eastern domain (right). (b) Same as (a) but for the likelihood of a fire ignition associated with a dry or wet lightning strike within a grid box.
Fig. 12. (a) Probability of dry lightning strikes igniting a fire in a grid box based on CAPE and 500 hPa geopotential heights with a holdover (lag) effect of 2 days in the western domain (left) and 3 days in the eastern domain (right). The observed CAPE and height values associated with fire ignition for 2000-2006 are shaded in color based on probability, observed values not associated with fire ignition are shaded in grey, and white areas do not contain observed data. (b) Same criteria as (a) but for the probability of a fire ignition in a grid box based on the number of dry lightning strikes and the number of consecutive dry days.