The Interannual Variability of Biomass Burning in North America using MODIS Data: Observations and Meteorological Influences

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Submitted to
the NASA Goddard Space Flight Center (GSFC)
Graduate Student Summer Program (GSSP)

August 08, 2008

Abstract:

Meteorological impacts on the interannual variability of wildfires in North America including Alaska are investigated using six years of the MODIS fire and Aerosol Optical Depth (AOD) products, the meteorological data from North American Regional Reanalysis (NARR), and the lightning data collected by the National Lightning Detection Network (NLDN). The North American continent is divided into four sub-regions (Alaska, U.S. west, Canada, and Québec) to study the relationships of MODIS fire counts, fire radiative power, and AOD with over 13 meteorological variables. Atmospheric instability and anomalies in the 500 hPa geopotential height field explain more than 60% of the interannual variability in wildfires in Alaska and Quebec; while in the western Unites States pre-season precipitation is a dominatant factor. Lightning strike data shows little correlation with fire counts in the western United States suggesting the importance of anthropogenic cause of fires in this region. Previously conceived relationships are also investigated between fires, instability, and smoke production. It is revealed that the Haines Index, a tool widely used for fire forecasting, are not sufficient and must used with 500mb geopotenial height anomalies to interpret the interannual varaiblity of fires in Boreal North America.

1. Introduction and Background

Wildfires burn large tracts of land across the North American continent each year and pose a major threat to the environment, economy, infrastructure, and even human life. Regardless of the type of vegetation, wildfires are a common occurrence in many regions and it is estimated that over 2.9 million ha yr^{-1} burned in the boreal regions of North America during the 1990s alone (Hicke et al., 2003). In addition to the treat on the ground, biomass burning ejects an enormous amount of particulate matter into the atmosphere creating concerns for air quality (e.g. Spracklen et al., 2007; Jordan et al., 2008). Wildfires in North America are ignited by either "natural" or anthropogenic sources and during the fire season of 2006, human caused fires burned 4,404,844 acres of land in the United States, at least 45% of the total acreage burned during the year (National Interagency Fire Center, 2008). Wildfires behave differently based on the local meteorology, topography, climate, and land use (e.g. Skinner et al., 1999; Stocks 2003; Westerling et al., 2003) which accentuates the importance of understanding how a fire is started and the conditions that are necessary for ignition.

In past decades, there have been several attempts to determine the potential for wildfire ignition and propagation based on atmospheric conditions. The Haines Index, developed in 1988, is a quick way to determine fire potential based on an integer scale from 1-6 and contains two main ingredients: moisture and stability (Haines, 1988). Moisture has always been recognized as a key component to fire ignition and the Haines Index utilizes the dew point depression at a specific pressure level based on surface elevation to reflect low-level moisture availability. In addition to instantaneous atmospheric moisture observations, the amount of precipitation prior to the start of the

fire season can be crucial for fire activity during the fire season in portions of North America. The western United States, especially the Southwest, contains an expanse of scrubland and grass which grows based on the antecedent moisture conditions creating fuel when it dries during the summer (Westerling et al., 2003).

Instability in the Haines Index is accounted for by using the lower-tropospheric lapse rate and is an important ingredient since unstable conditions commonly lead to higher smoke plumes, transport of burning embers, stronger inflow to the fire, and a higher chance of "extreme fire behavior" (Werth and Ochoa, 1993). The Haines Index does take the surface elevation into account but does not consider the low-level wind speed, fuel moisture, fuel type, and fuel availability. Despite the drawbacks, the Haines Index is very popular with forecasters and local emergency management but many do not understand the fundamental components and make judgment based only on the number of the index (Potter et al., 2008). Even with instability as a fundamental component of the renowned tool for fire forecasting, there has never been an attempt to quantitatively assess the importance of this variable in fire ignition, especially over long temporal and spatial scales.

Instability is paramount in determining the potential for convection and lightning which is a major source of wildfire ignition, especially in boreal North America. If an unstable environment exists, updrafts can become very strong and in combination with a source of moisture, result in thunderstorm development. These thunderstorms can produce "dry lightning" to ignite fires if any of the following four scenarios occur: (a) the thunderstorm is high-based and 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 is not allowed to accumulate due to the velocity of the storm (Rorig and Ferguson, 2002). Nevertheless, lightning strikes are unlikely to cause fire ignition unless an unstable environment exists. Rorig and Ferguson found that fires corresponded better with instability than with lighting strikes for several localized fire cases in the western United States during the summer of 2000. Conversely, little work has been done to qualitatively or quantitatively investigate the relationship between observed lighting strikes, fire locations, and instability across North America over seasonal or longer time scales.

Biomass burning in North America produces large smoke plumes that increase the concentration of atmospheric aerosols (Spracklen et al., 2007) and can be transported thousands of miles (Damoah et al. 2005). The height and morphology of the smoke plume has also been linked to the local meteorological conditions at the time of the fire, especially the atmospheric stability profile (Kahn et al., 2007). Over time, atmospheric stability has been used to explain a wide array of wildfire situations raging from lightning strikes for ignition to plume height and transport; but the question of whether an unstable fire season produces more intense or a greater quantity of fires has yet to be answered.

Large scale circulation pattern anomalies have also been linked to fire activity in the North American boreal regions. Skinner et al. (1999) investigated the 500 hPa height anomalies in Canada and the relation to fire activity. The Rocky Mountains, bisecting western Canada from the Alaska border to the Pacific Northwest, were found to create a ridge in the height field over western Canada and a trough over eastern Canada during the warm season mean. Anomalously high heights during the fire season were better correlated with a greater area burned than anomalously low heights. It is hypothesized in

this study that height anomalies at 500 hPa by themselves do not entirely explain the higher number of observed fires; but rather the associated changes in atmospheric stability, temperature, precipitation, and cloud cover actually play the main role in fire behavior. Furthermore, the variation in height fields over Alsaka has not been explored in previous studies.

While the conditions necessary for large fire seasons and smoke transport have been explored in several early studies, a comprehensive and quantitative assessment has not been conducted of the importance of each meteorological variable to the regional and interannual variability of fires throughout North America. Furthermore, most of past studies used ground reports of the number of fires or estimates of area burned; the uncertainties associated with these dataset are likely to be large. With the advancement in satellite remote sensing, fires and burned area are now monitored routinely with unprecedented accuracy from NASA's EOS sensors such as MODerate Resolution Imaging Spectroradiometer (MODIS). Using multi-year MODIS fire products (dating back to Feb 2000) and a comprehensive archive of meteorological variables, this study will attempt to quantitatively assess the role of the physical mechanisms responsible for the interannual variability of wildfires and smoke in North America both spatially and temporally for the fire seasons of 2000-2006. Such analysis will provide insight to the variables that are most important at a regional scale to fire ignition, growth, and propagation.

2. Data

The MODIS sensor aboard the Terra satellite (launched 19 December 1999) provided all of the fire data used in this study and is a modified version of data set used in

Ichoku et al. (2008). Terra MODIS characterizes globally the number, location, and radiative power (FRP) of fires twice per day achieving near global coverage each day. Fires are detected using radiance measurements in the 4 µm and 11 µm channels while fire radiative power is calculated using only the 4 µm channel (Kaufman et al., 1998). The FRP is the radiative energy rate of release per unit time (Kaufman et al., 1998; Jordan et al., 2008). In contrast to earlier sensors such as the Advanced Very High Resolution Radiometer (AVHRR), MODIS is currently the only operational satellite sensor designed to specifically measure FRP (Ichoku et al., 2008). The MODIS algorithms are periodically updated creating several different versions used to create data collections and collection 4 data was used in this study (Giglio et al., 2003; Ichoku et al., 2008). Since this study focuses on interannual variability, only the Terra daytime overpass data was used because (a) it provides the longest available data set (2000-2006); and (b) the highest diurnal concentration of fire pixels in North America is found to occur in the early afternoon (Ichoku et al., 2008).

In order to address smoke aerosol loading, MODIS Collection 5 aerosol optical depth (AOD) at 500 nm was also used. In particular, the level 3 monthly mean product from the MODIS sensor on the terra satellite (MOD08_M3). The MODIS AOD product uses separate algorithms to retrieve the aerosol information over land and water (Remer et al., 2005). The product used here is the combination of both the land and water output. It is important to note that the AOD can only be retrieved during daytime, cloud-free conditions which also favors the use of daytime fire data for analysis and comparison.

Meteorological data were obtained using the North American Regional Reanalysis (NARR) archived at the National Climatic Data Center (NCDC). The NARR

assimilates a variety of observational data into a 45 layer, 32 km grid dating back to 1979 (Mesinger, 2006). At a higher resolution than the global reanalysis, the NARR provides a more detailed reanalysis of standard atmospheric observed variables, derived variables, and sub-surface variables (Ebisuzaki, 2004). A collection of monthly means for 13 NARR variables covering soil and atmospheric moisture, instability, precipitation, etc. were used in this study for 2000-2006.

The National Lightning Detection Network (NLDN) was used to obtain cloud-to-ground lightning strikes for the continental United States (CONUS). The point location of each lightning strike is found through geo-location using the Improved Performance Combined Technology (IMPACT) Antenna system (Cummins et al., 1998). Over 150 IMPACT stations (Fig. 1) are used to ascertain the location, polarity, and number of individual strikes within one lightning flash (multiplicity). The IMPACT sensors take into account both direction finding and time of arrival using several sensors to detect the location of a single strike. For the purposes of this study, each large lightning strike, regardless of the multiplicity, was considered as a single strike.

3. Time Periods and Regions

In order to gain a regional perspective on variability, North America was subdivided into four smaller regions (Fig. 2). The boundaries of these regions follow Ichoku et al. (2008) as part of a global study on wildfire patterns and intensity where 36 sub-regions were used. Each region was created such that it contained a dominant ecosystem type. The Boreal forests of North America cover large expanses of land in Alaska and Canada and this area was broken into three regions (Alaska, Canada, and Québec) while the western United States was left as one region covering a mix of forest

and large tracts of scrubland (US West). The sub-regions are not uniform in size and the boundaries, boxed area, and total land area for each region are presented in table 1.

Each region in North America was analyzed comparatively and independently for several fire related and meteorological variables. The monthly aerial average was used for each variable since this study is focuses on broad regions of the North American Continent. A statistical analysis was performed to determine the correlation and significance of each variable by region. Due to different climatic conditions between the northern regions and the US West, the fire season was defined as June-August in the three northern regions and June-October in the US West.

4. Results and Discussion

4.1 Fire Counts, FRP, and AOD

Before comparing fires with meteorology, it was pertinent to investigate the number and intensity of fires in each region and if there was a correlation with smoke (AOD). In order to better represent the emissive power of the fires, the FRP flux (Wm^{-2}) was computed by dividing the FRP (W) by the total land area within each region. The FRP flux and fire counts were then regionally correlated with AOD to determine if a higher number of fires resulted in more smoke (Table 2). The FRP flux was found to be slightly better at describing smoke production than the observed fire pixels in most regions. FRP flux correlated with AOD in Alaska, Canada, and the US West all showed an $R > 0.70$ while Québec showed little correlation ($R = 0.02$). FRP flux and AOD were strongly correlated in Alaska ($R = 0.95$) suggesting that a large amount of smoke produced in this region remains within the boundaries of the region (Fig. 3). The issue of aerosol transport may explain why Québec does not conform to the other regions. For

example, the largest number of fires in this region occurred in 2002 where the prevailing flow during the largest fire event transported the smoke well into the interior of the eastern United States (Sapkota et al., 2005)

4.1 Meteorological Analysis

The 13 meteorological variables from the NARR were correlated with the number of fire pixels (fire counts) and FRP flux to quantitatively discern which variables were regionally important for fire starts. Tables 3 and 4 present the results of the correlations with shading indicating $|R| \geq 0.70$ and the level of significance. It is clear that discrepancies exist between geographic regions, fire counts, and FRP Flux. In both Alaska and Québec, the correlations using fire counts and FRP flux produced the same variables of interest with similar R and R^2 values however, FRP Flux for those variables tested at a higher level of significance (95%). This suggests that the important variables in Alaska and Québec can explain both the number and intensity of fires. The Canada region showed no conformity between fire counts and FRP Flux and the US West region was only consistent with November-May Precipitation.

4.1.1. Boreal Regions

Whether using fire counts or FRP flux, convective available potential energy (CAPE) was immediately evident as an important variable in both Alaska and Québec with R = 0.97 and R = 0.80 respectively when considering fire counts (fire counts will be used for comparison). CAPE is basically a measure of instability with higher values indicating more unstable conditions and the potential for stronger updrafts or higher buoyancy. Between 2000 and 2006, Alaska experienced a wide range in the number of fire counts with very few in 2000 and 2001 but nearly 20,000 in the remarkable fire

season of 2004. In Québec, the highest number of fire counts occurred in 2002 with a smaller peak in 2005. The years with the greatest quantity of fire counts coincide very well with the highest CAPE anomalies in both Alaska and Québec (Fig. 4). In order to investigate this phenomenon spatially, fire counts and CAPE anomalies were plotted for each region. The CAPE anomaly is computed by the NARR using the climatological mean from 1979 to 2001. Alaska experienced unprecedented anomalously high CAPE values in the central and eastern portions of the region during the fire season of 2004. As expected, the majority of observed fire counts were located within the region of instability (Fig. 5a,b). Similarly, a collocation of fire counts and anomalously high CAPE occurred in central Québec during the fire season of 2002 (Fig. 5c,d). In years with relatively few fire counts, such as 2006 in Alaska and 2004 in Québec, both regions experienced lower CAPE values or more stable conditions (Figs. 6a-d).

In contrast to Alaska and Québec, negative correlations between CAPE and fire counts were discovered in Canada with R = -0.67 (Fig. 7). In Canada, the large east/west dimension of the regional box defined earlier played a role in the outcome of the correlation. As with Alaska, the highest quantity of fires occurred in 2004, however; this was the year with the least amount of CAPE in the region. The reason for this has to do with the geographic distribution of the positive CAPE anomaly and fires versus the negative CAPE anomaly. For example, the majority of fire counts and the positive CAPE anomalies in 2004 were located in the western third of the region near the Yukon Territory with a vast region of very low CAPE anomalies in the reminder of the region (Fig. 8). Therefore, the negative CAPE anomaly (stable region) outweighed the smaller region of instability and fires. It is also pertinent to note that unlike Alaska and Québec,

the delineation of fires between areas of high and low CAPE anomalies is not exact and a relatively high concentration of fire counts were found within the region of negative CAPE anomalies.

The reason for the mysterious distribution of CAPE and fire counts in the Canada region is associated with larger-scale processes. As described earlier, the 500 hPa geopotential height field has been linked to the number of fires with anomalously high heights corresponding to more fires (Skinner et al., 1999). The mean 500 hPa height pattern for June-August in North America is displayed in Fig. 9 and shows a ridge over the western third of the continent and a trough in the eastern portion which is a reflection of the effect of the topography (Rocky Mountains). The Alaska (Québec) region is typically dominated by a ridge (trough) allowing CAPE anomalies to be easily assessed while the Canada region contains a portion of both features.

It is clear that the height gradient between ridge and trough bisects the Canada region in the mean thereby creating a highly variable environment with respect to geopotential height. A ridge in the large-scale pattern is associated with warmer temperatures, less cloud cover, and the potential for a convectively unstable environment while a trough is associated with cooler, unsettled weather. Daily and weekly variations in this ridge/trough pattern are commonplace, which helps to explain why fire counts do not end abruptly at the edge of the high CAPE anomaly. It is possible that the ridge axis moved to the east for a period of time during the 2004 fire season allowing warm, unstable air to spread over central Canada and increase the potential for lightning, the major cause of fires in boreal North America (Stocks et al., 2003). Furthermore, the amplitude of the height pattern was greatly increased in 2004 (Fig. 10) explaining how

extremely strong positive and negative CAPE anomalies can exist adjacent to each other. When the region of western Canada with the highest concentration of fire counts and positive CAPE anomalies was combined with the Alaska region, a correlation between fire counts and CAPE resulted in R = 0.99. It should also be emphasized that fires do collocate with positive CAPE anomalies in Canada as seen in 2004 but do not perfectly conform to the region of the CAPE anomaly due to the variability of the height gradient. For example, an area of positive CAPE anomalies existed in the eastern portion of the Canada region during the fire season of 2006 and the highest concentration of fire counts was also found in this area but a smaller number of fire counts were spread throughout central Canada around the positive CAPE anomaly (Fig. 11)

By investigating the discrepancies in the Canada region, it became clear that instability alone does not explain the number of fire counts in each region. In order to experience anomalously high values of CAPE, a ridge must be present in the 500 hPa height field which also has implications on temperature, precipitation amount, cloud cover, etc. In addition to CAPE, the Alaska region displayed strong correlations with surface temperature (R = 0.95) and 500 hPa height (R = 0.83). This region is typically dominated by moist conditions and a great deal of stratus-type cloud cover however, when an anomalously strong ridge develops over the region, such as in 2004, temperatures warm drastically and cloud cover diminishes. These conditions allow the biomass to dry while isolated airmass-type thunderstorms develop and spark fires.

Instability and the 500 hPa geopotential height pattern also have implications on smoke production and transport. As mentioned earlier, unstable conditions can enhance the height of the smoke plume (Kahn et al., 2007). Furthermore, an unstable environment

would concurrently increase the inflow into a fire allowing both the fire itself and the associated smoke plume to intensify. This effect is well represented in the Alaska region where CAPE correlates well with the FRP Flux (R = 0.96) and AOD (R = 0.87, not shown) suggesting that higher CAPE increases the smoke produced and the intensity of fires in this region. The mean 500 hPa geopotential height pattern also becomes important in these cases as the smoke plume reaches higher into the atmosphere. In the middle and upper levels of the atmosphere, the wind is assumed to be geostrophic, or aligned with the height contours. Therefore, unstable conditions could result in the smoke plume penetrating into the upper-level winds and being transported with the geostrophic flow over a great distance. This is a possible explanation of why smoke from the large fire events in the boreal regions travels thousands of miles and smoke in smaller events typically remains close to the source. In the seven years examined in this study, all of the fire seasons with a high number of fire counts, such as 2004 in Alaska and 2002 in Québec, showed anomalously high instability (CAPE) and were also events where smoke was transported over a great distance (e.g. Sapkota et al., 2005; Duck et al., 2007).

Surprisingly, relative humidity (RH) and fire season precipitation showed a rather weak negative correlation in the boreal regions. Moisture parameters were expected to show negative correlations but did not correlate as strongly as expected especially since moisture is a key component in the Haines Index (Haines, 1988). This suggests that instability is more important in explaining the number of fires in the boreal regions than moisture. Furthermore, instability is ultimately responsible for lightning, the main cause of fires in these regions; nevertheless, the biomass must be sufficiently dry for lighting-caused ignition to become an issue.

4.1.2. Western United States

Striking differences exist when considering important fire related variables in the US West region when compared to the boreal regions. In the US West region, pre-season precipitation, the total accumulated precipitation (both rain and snow) between November and May is very important (R = 0.83) in describing the number of fire counts. This confirms the results of Westerling et al. (2003) who showed the importance of antecedent moisture. The US West, aside from areas with a large summer monsoon influence, receives most of its annual in the winter months. It is this moisture that allows the low-growing shrubs and grass common in many areas, especially the Southwest, to grow in the spring months. If there is a significant amount of pre-season precipitation, then the biomass will provide plentiful fuel for the following fire season as it begins to dry during the summer months hence the positive correlation.

Aside from pre-season precipitation, few meteorological variables correlated well with fire counts in the US West. This is partly due to the fact that many fire starts are anthropogenically started, whether by accident or intentionally and may also be related to the varying vegetation types and monsoon influences contained within the regional box. The impact of anthropogenic fire starts can be identified using the 2003 fire event in southern California. This was a Santa Ana event which created a very stable, down-slope wind environment when the fires broke out. It would have been nearly impossible for lightning to spark fires in this type of setup dominated by clear skies and dry conditions, but many fires still broke out leaving humans as the only possible cause. Situations like this help to explain why CAPE showed a weak negative correlation with fire counts in the US West and how other variables may not be completely representative.

4.2 Lightning Analysis

A basic analysis of lighting strikes for June – October (2000-2006) was also performed for the US West region using the NLDN data which is only available for the CONUS. As with the other meteorological variables, lightning strikes were compared with the number of fires in the region (Fig. 12). This was accomplished by summing every individual lighting strike in the region for the entire fire season. Lightning strikes and fire counts showed a much stronger correlation than expected at this large scale (R = 0.45) since anthropogenic influences were assumed to be large and many thunderstorms, especially in the monsoon months, produce lightning but do not start fires. In order to explore the role of lightning at a smaller spatial scale, a 1° x 1° grid plot was constructed and a correlation between fire counts and lightning was performed for each grid (Fig. 13). A limit was set such that at least two years of fire count data was needed to compute the correlation or the grid was left blank. Most grids showed a weak correlation as expected, but several grids correlated with R > 0.80. A detailed comparison with lighting in boreal regions is left for future study but it is assumed that these regions will show a much stronger correlation between lightning and fire counts since the anthropogenic factor is smaller.

5. Summary and Future work

As components of the Haines index, instability and moisture have been recognized as major factors in wildfire ignition for many years (Haines 1988). The results presented in this study suggest that instability is undoubtedly a very important meteorological variable in describing the interannual variability of wildfires in North America and perhaps, the most important in boreal regions. Moisture was found to be

less important on the regional scale used here. Fire seasons with anomalously high instability in Alaska and Québec were found to have the greatest quantity of fire counts and a higher FRP Flux suggesting more intense fires. In addition, fire counts, FRP flux, and AOD showed a strong correlation with instability in Alaska suggesting a link between instability and smoke production.

Skinner et al. (1999) discovered a link between 500 hPa height anomalies and the number of observed fires however; the results from this study suggest that the 500 hPa height pattern is what sets the stage for an unstable environment to occur. Therefore, it is the combination of both a favorable 500 hPa pattern and low-level instability that is responsible for the years with a large number of fires in boreal North America. Anomalously high CAPE, 500 hPa geopotential heights, and the largest number of fire counts were collocated in nearly every year for each boreal region. The Canada region as a whole did not conform to the results in Alaska and Quebec since the variable boundary between ridge and trough in the 500 hPa gepotential height pattern was located in this region.

The US West region showed a strong correlation between fire counts and pre-season precipitation confirming the results of Westerling et al. (2003) and showed that remotely sensed fire data yielded similar results to the ground observations used in that study. Aside from a negative correlation when using CAPE, the remainder of the meteorological variables in this region did not display a strong correlation with fire counts possibly due to a high number of anthropogenic fire starts. Unlike Canada, the negative correlation with CAPE in the US West is likely due to human influences,

especially during Santa Ana events which produce many fire counts and are not associated with lightning and high instability.

The gridded correlation between lightning strikes and fire counts displayed a mix of highly correlated grids and grids with little correlation. The US West region as a whole showed a slight positive correlation between lightning strikes and fire counts suggesting that lightning can only explain a certain portion of fires and other causes, such as humans, play a role. It is obvious that the lightning results presented here are only a general overview of the entire situation. More analysis is needed to remove the effects of lightning associated with “wet” thunderstorms and consider only “dry lightning” if possible. Also, a thorough comparison with lightning strikes in Alaska and Canada is needed to fully understand the role of lightning in fire starts throughout North America. Another consideration is that a lightning strike is an instantaneous phenomenon and the resulting fire counts may last for days.

Now that the role of instability and the large-scale circulation is beginning to be realized, it seems pertinent to define regions based on the large-scale meteorology rather than the biomass and see if the same results are achieved. It is clear from many previous studies that smoke plume height, transport, and the meteorological conditions are related, but the question of how fires in one region affects another region is not fully understood. Therefore, this is an ongoing study that will require additional analysis to fully comprehend the many processes that affect the interannual variability of biomass burning in North America

Acknowledgements

Lightning Data:

NLDN data provided by the NASA Lightning Imaging Sensor (LIS) instrument team and the LIS data center via the Global Hydrology Resource Center (GHRC) located at the Global Hydrology and Climate Center (GHCC), Huntsville, Alabama through a license agreement with Vaisala, Inc. The data available from the GHRC are restricted to LIS science team collaborators and to NASA EOS and TRMM investigators.

Special Thanks:

I would like to thank to my mentors at NASA GSFC: Dr. Lorraine Remer, Dr. Charles Ichoku, and Dr. Jun Wang for providing guidance, data, and support for this project. I would also like to thank Valerie Casasanto and Valerie Buxton for helping to make the summer go smoothly. I am very grateful for the opportunity to work with the brilliant staff at NASA Goddard and the knowledge I have gained from this wonderful experience.

References

Cummins, K. L., E. P. Krider, et al. (1998). "The US National Lightning Detection Network (TM) and applications of cloud-to-ground lightning data by electric power utilities." Ieee Transactions on Electromagnetic Compatibility **40**(4): 465-480.

Damoah, R., N. Spichtinger, R. Servranckx, M. Fromm, E. W. Eloranta, and P. J. I. A. Razenkov, M. Shulski, C. Forster, and A. Stohl (2005). "Transport Modelling of a pyro-convection event in Alaska." Atmospheric Chemistry and Physics Discussions **5**: 6186-6214.

Duck, T. J., B. J. Firanski, et al. (2007). "Transport of forest fire emissions from Alaska and the Yukon Territory to Nova Scotia during summer 2004." Journal of Geophysical Research-Atmospheres **112**(D10).

Ebisuzaki, W. (2004). National Climatic Data Center Data Documentation for NOAA Operational Model Archive and Distribution System (NOMADS) North American Regional Reanalysis. NOAA. Camp Springs, MD**:** 1-11.

Giglio, L., J. Descloitres, et al. (2003). "An enhanced contextual fire detection algorithm for MODIS." Remote Sensing of Environment **87**(2-3): 273-282.

Haines, D. A. (1988). "A lower atmosphere severity index for wildland fire." National Weather Digest(13): 23-27.

Hicke, J. A., G. P. Asner, et al. (2003). "Postfire response of North American boreal forest net primary productivity analyzed with satellite observations." Global Change Biology **9**(8): 1145-1157.

Ichoku, C., L. Giglio, et al. (2008). "Global characterization of biomass-burning patterns using satellite measurements of fire radiative energy." Remote Sensing of Environment **112**(6): 2950-2962.

Jordan, N. S., C. Ichoku, et al. (2008). "Estimating smoke emissions over the US Southern Great Plains using MODIS fire radiative power and aerosol observations." Atmospheric Environment **42**(9): 2007-2022.

Kahn, R. A., W. H. Li, et al. (2007). "Aerosol source plume physical characteristics from space-based multiangle imaging." Journal of Geophysical Research-Atmospheres **112**(D11).

Kaufman, Y. J., C. O. Justice, et al. (1998). "Potential global fire monitoring from EOS-MODIS." Journal of Geophysical Research-Atmospheres **103**(D24): 32215-32238.

Mesinger, F., G. DiMego, et al. (2006). "North American Regional Reanalysis." Bulletin of the American Meteorological Society **87**(3): 343-360.

Potter, B. E., J. A. Winkler, et al. (2008). "Computing the low-elevation variant of the Haines index for fire weather forecasts." Weather and Forecasting **23**(1): 159-167.

Remer, L. A., Y. J. Kaufman, et al. (2005). "The MODIS aerosol algorithm, products, and validation." Journal of the Atmospheric Sciences **62**(4): 947-973.

Rorig, M. L. and S. A. Ferguson (2002). "The 2000 fire season: Lightning-caused fires." Journal of Applied Meteorology **41**(7): 786-791.

Sapkota, A., J. M. Symons, et al. (2005). "Impact of the 2002 Canadian forest fires on particulate matter air quality in Baltimore City." Environmental Science & Technology **39**(1): 24-32.

Skinner, W. R., B. J. Stocks, et al. (1999). "The association between circulation anomalies in the mid-troposphere and area burned by wildland fire in Canada." Theoretical and Applied Climatology **63**(1-2): 89-105.

Spracklen, D. V., J. A. Logan, et al. (2007). "Wildfires drive interannual variability of organic carbon aerosol in the western US in summer." Geophysical Research Letters **34**(16).

Stocks, B. J., J. A. Mason, et al. (2002). "Large forest fires in Canada, 1959-1997." Journal of Geophysical Research-Atmospheres **108**(D1).

Werth, P. and R. Ochoa (1993). "THE EVALUATION OF IDAHO WILDFIRE GROWTH USING THE HAINES INDEX." Weather and Forecasting **8**(2): 223-234.

Westerling, A. L., A. Gershunov, et al. (2003). "Climate and wildfire in the western United States." Bulletin of the American Meteorological Society **84**(5): 595-+.

Tables

Table 1. Fire regions selected for this study shown as red boxed in Fig. 2 (Ichoku et al., 2008).

Name	Min Lon	MaxLon	Min Lat	Max Lat	Area (km^2)	Land (km^2)
Alaska	-170	-140	50	75	4272368	1512008
Canada	-140	-80	50	70	7420930	5376155
Québec	-80	-55	45	65	3543403	1998438
US West	-135	-105	30	50	4217487	3183368

Table 2. Correlation coefficients in different regions for AOD respectively with fire counts ($R_{AOD\text{-}FC}$) and fire radiative power ($R_{AOD\text{-}FRP}$).

Region	$\mathbf{R}_{AOD\text{-}FC}$	$\mathbf{R}_{AOD\text{-}FRP}$
Alaska	0.93	0.95
Canada	0.90	0.80
Québec	0.07	0.02
US West	0.24	0.72

. Table 3. Correlations between meteorological variables and fire counts.

CORRELATIONS	ALASKA		QUÉBEC		CANADA		US WEST	
FIRE COUNTS	R	R^2	R	R^2	R	R^2	R	R^2
Fire Season	JJA		JJA		JJA		JJASO	
Convective Precip.	0.68	0.46	-0.35	0.12	0.43	0.18	0.29	0.08
Horiz. Moisture Divergence	0.69	0.47	0.50	0.25	0.62	0.39	0.83	0.69
850 hPa Wind Speed	-0.68	0.46	0.52	0.27	0.03	0.00	-0.20	0.04
Nov-May Snowfall	0.23	0.05	-0.31	0.10	-0.11	0.01	0.05	0.00
Fire Season Precipitation	-0.46	0.21	-0.59	0.35	-0.04	0.00	0.33	0.11
Nov-May Precipitation	-0.05	0.00	-0.04	0.00	0.58	0.34	0.83	0.69
Relative Humidity (sfc)	-0.42	0.18	-0.34	0.12	0.20	0.04	-0.15	0.02
Soil Moisture (0-200cm)	0.40	0.16	-0.22	0.05	0.35	0.12	0.63	0.40
Lq. Vol. Soil Moisture (0-10cm)	0.19	0.04	-0.46	0.21	0.38	0.14	0.47	0.22
10m Temperature	0.95	0.90	0.13	0.02	-0.14	0.02	0.36	0.13
10m Temperature (Jan-May)	0.25	0.06	-0.33	0.11	-0.15	0.02	-0.11	0.01
Lifted Index (LI)	-0.68	0.46	0.39	0.16	0.30	0.09	0.49	0.24
CAPE	0.97	0.94	0.78	0.60	-0.67	0.45	-0.79	0.62
TKE	-0.88	0.78	0.71	0.51	-0.31	0.09	-0.44	0.19
Precipital Water	0.65	0.43	-0.12	0.01	-0.70	0.49	0.28	0.08
500 hPa Height	0.83	0.69	0.65	0.42	0.55	0.31	0.52	0.27

$\lvert R \rvert \geq 0.70$	90% significant	95% significant

Table 3. Correlations between meteorological variables and fire counts.

Table 4. Correlations between meteorological variables and FRP flux.

CORRELATIONS	ALASKA		QUÉBEC		CANADA		US WEST	
FRP Flux	R	R^2	R	R^2	R	R^2	R	R^2
Fire Season	JJA		JJA		JJA		JJASO	
Convective Precip.	0.68	0.46	-0.37	0.14	0.36	0.13	-0.14	0.02
Horiz. Moisture Divergence	0.68	0.46	0.50	0.25	0.67	0.44	0.58	0.34
850 hPa Wind Speed	-0.60	0.36	0.53	0.28	0.37	0.14	-0.51	0.26
Nov-May Snowfall	0.19	0.04	-0.32	0.10	-0.19	0.04	-0.40	0.16
Fire Season Precipitation	-0.42	0.18	-0.61	0.38	-0.15	0.02	0.05	0.00
Nov-May Precipitation	-0.12	0.01	-0.01	0.00	0.38	0.14	0.80	0.63
Relative Humidity (sfc)	-0.40	0.16	-0.35	0.12	0.00	0.00	-0.39	0.15
Soil Moisture (0-200cm)	0.41	0.16	-0.20	0.04	0.38	0.14	0.14	0.02
Lq. Vol. Soil Moisture (0-10cm)	0.23	0.05	-0.47	0.22	0.33	0.11	0.00	0.00
10m Temperature	0.95	0.90	0.15	0.02	0.13	0.02	0.36	0.13
10m Temperature (Jan-May)	0.25	0.06	-0.28	0.08	-0.22	0.05		0.00
Lifted Index (LI)	-0.69	0.47	0.34	0.11	0.20	0.04	0.42	0.17
CAPE	0.96	0.93	0.80	0.65	-0.73	0.54	-0.46	0.22
TKE	-0.87	0.76	0.73	0.54	-0.05	0.00	-0.30	0.09
Precipital Water	0.69	0.47	-0.14	0.02	-0.48	0.23	0.35	0.12
500 hPa Height	0.83	0.70	0.59	0.35	0.73	0.54	0.55	0.30

|R| ≥ 0.70	90% significant	95% significant

Figures

Fig. 1. Location of the National Lightning Detection Network (NLDN) IMPACT (triangles) or upgraded IMPACT (circles) sensors.

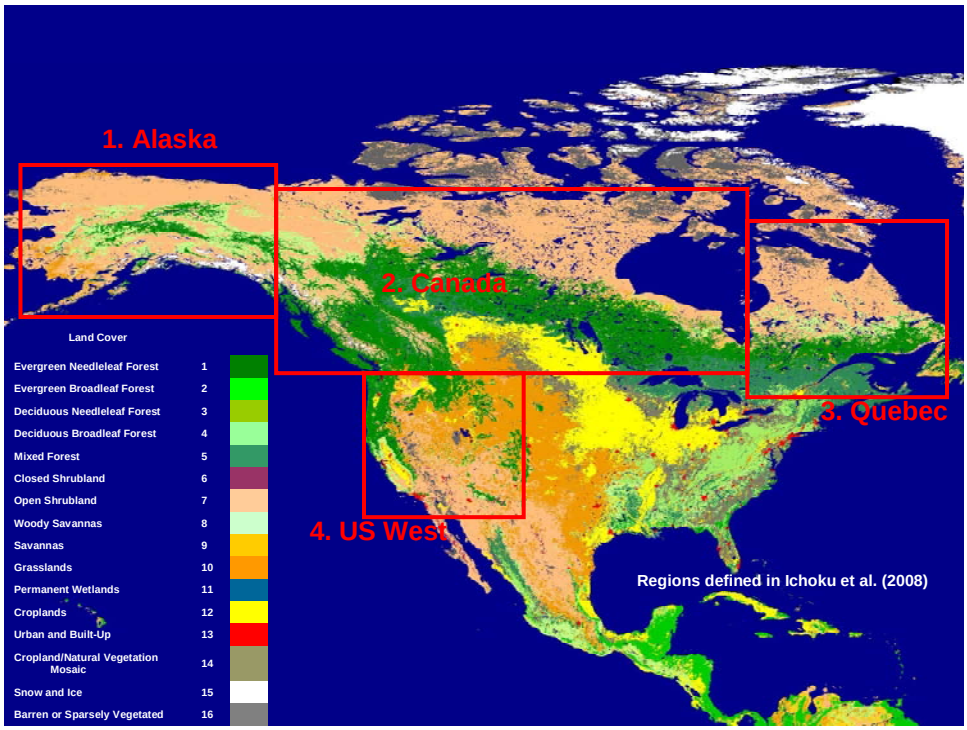

Fig. 2. Global MODIS derived ecosystem map. Red boxes delineate the regions defined for analysis in this study and to not conform to political boundaries (Ichoku et al., 2008).

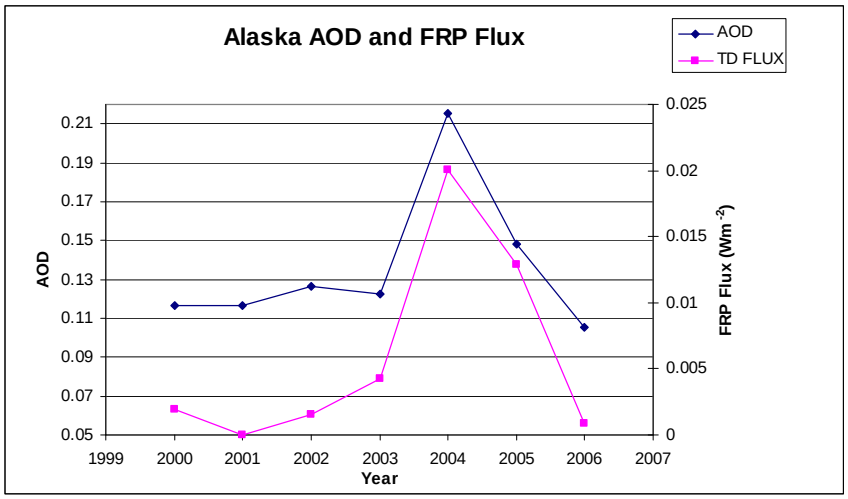

Fig. 3. AOD and FRP Flux in Alaska for the years 2000-2006.

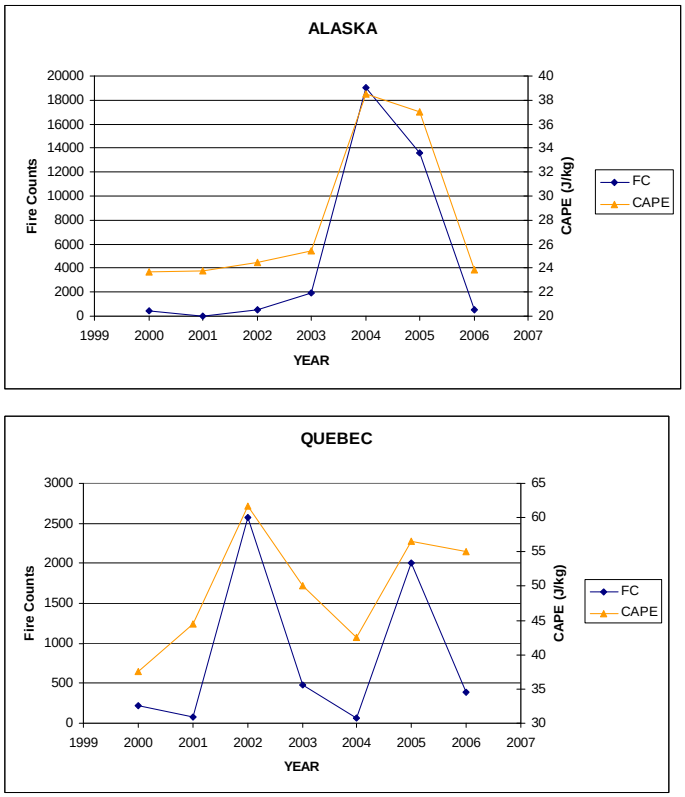

Fig. 4. Fire season CAPE and fire counts for Alaska (top) and Québec (bottom) during 2000-2006.

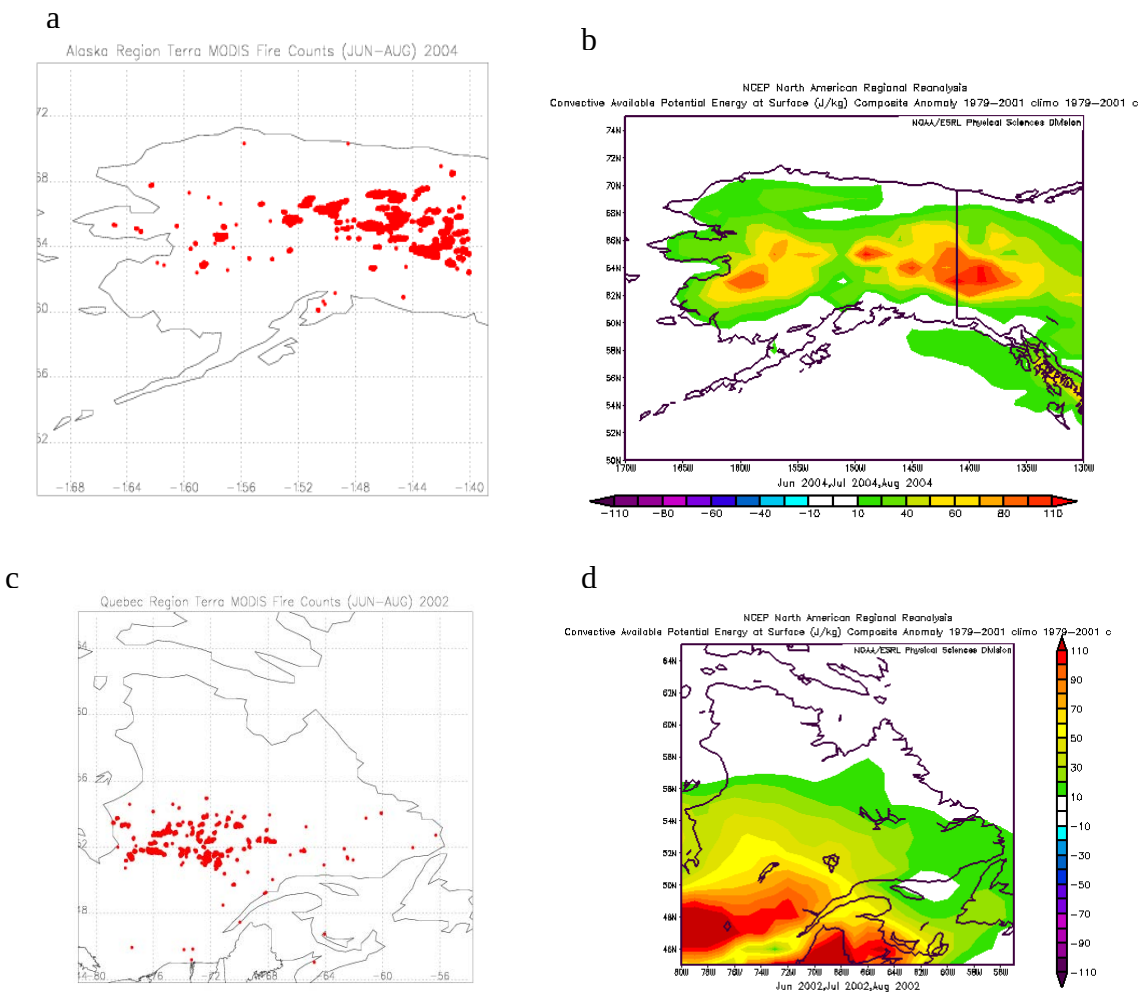

Fig. 5. Fire season spatial distribution of fire counts and CAPE for Alaska (a,b) and Québec (c,d) for a high-fire year (Jun.-Aug., 2002).

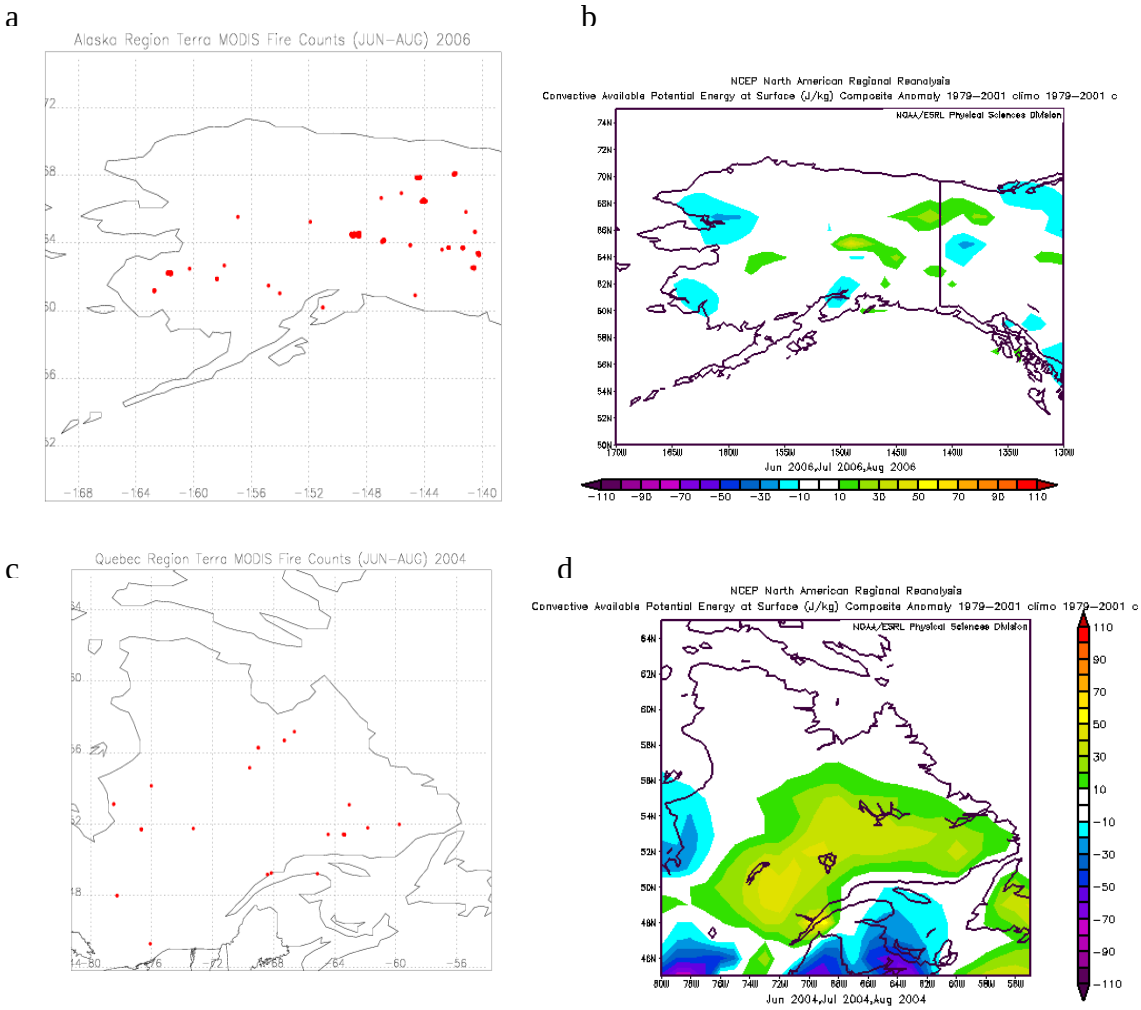

Fig. 6. Fire season spatial distribution of fire counts and CAPE for Alaska (a,b) and Québec (c,d) for a low-fire years (Jun.-Aug., 2004).

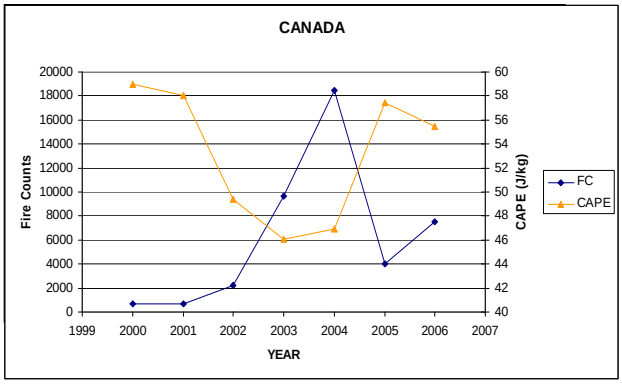

Fig. 7. Fire season CAPE and fire counts for Canada (2000-2006).

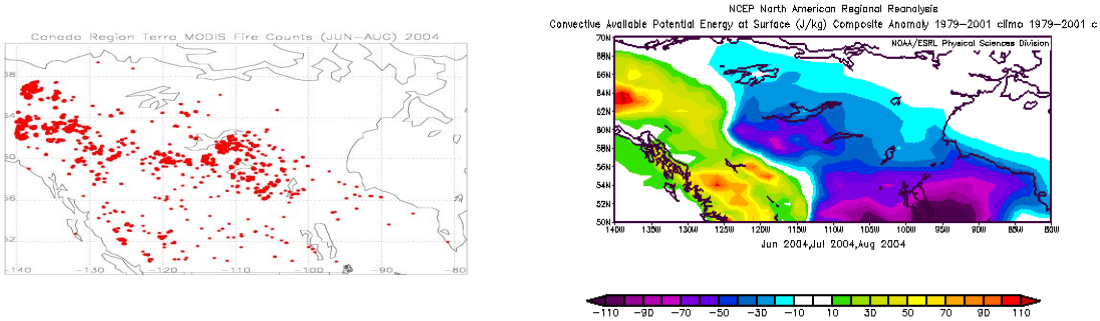

Fig. 8. Fire season spatial distribution of fire counts (left) and CAPE (right) for Canada in 2004

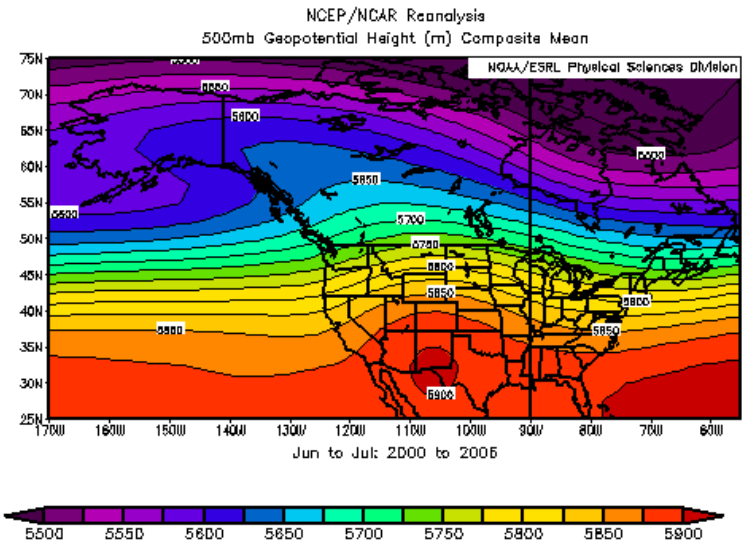

Fig. 9. Mean 500 hPa geopotential height pattern for North America for Jun.-Oct. (2000-2006).

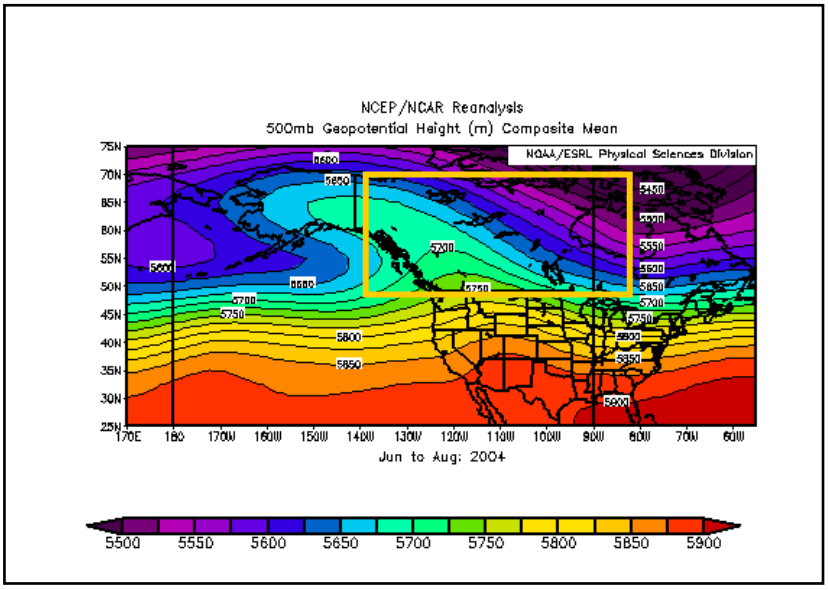

Fig. 10. Mean 500 hPa geopotential height pattern for North America for Jun.-Oct. of 2004. Yellow box delineates the boundaries of the Canada region.

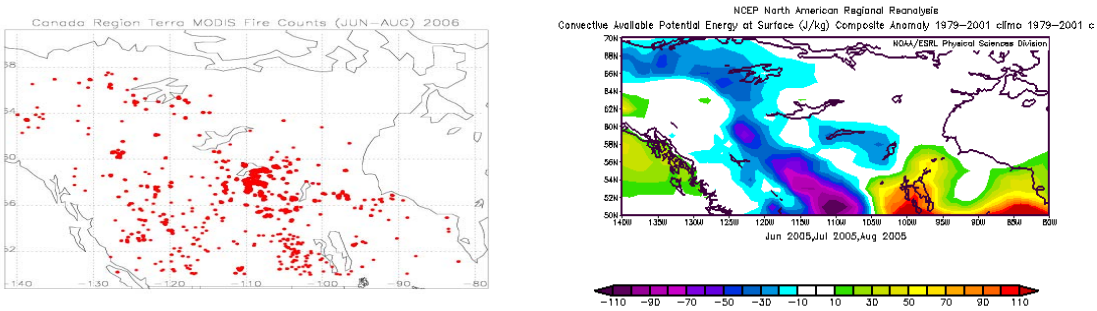

Fig. 11. Fire season spatial distribution of fire counts (left) and CAPE (right) for Canada in 2006 showing the result of a shift in the anomalously unstable region.

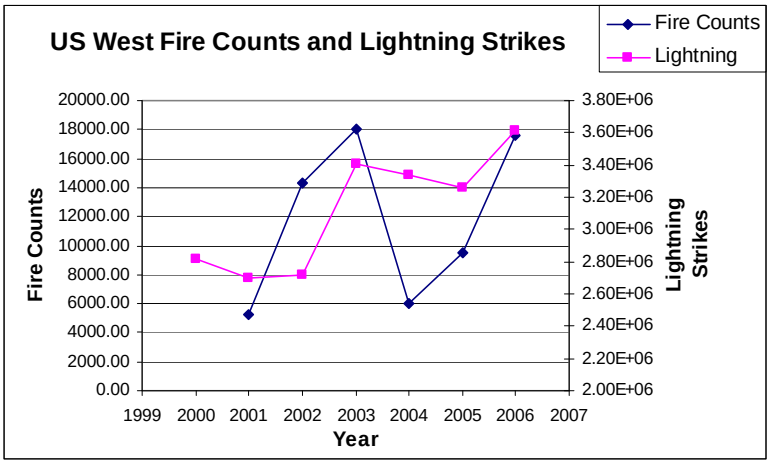

Fig. 12. Fire season lightning strikes and fire counts for the US West (2000-2006). Fire count data for 2000 was incomplete.

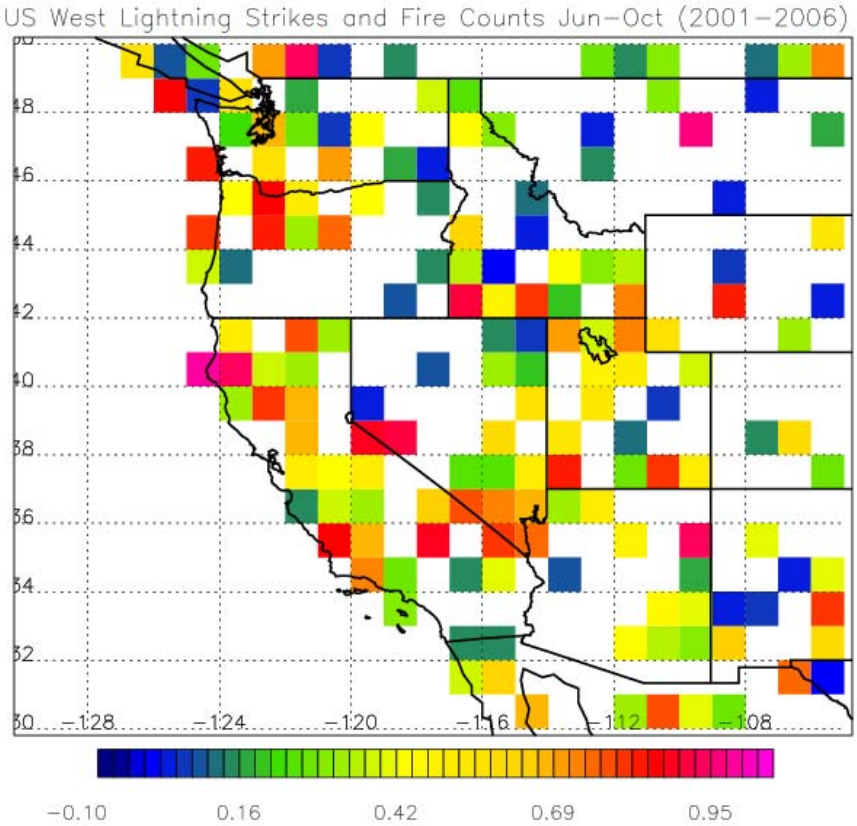

Fig. 13. Gridded 1° x 1° correlation plot for lightning strike strikes and fire counts in the US West (2001-2006).