ARCTIC
VOL. 59, NO. 2 (JUNE 2006) P. 211–221

Lightning and Fires in the Northwest Territories and Responses to Future Climate Change

B. KOCHTUBAJDA,[1,2] M.D. FLANNIGAN,[3] J.R. GYAKUM,[4] R.E. STEWART,[4] K.A. LOGAN[3] and T.-V. NGUYEN[1,5]

(*Received 22 June 2004; accepted in revised form 12 September 2005*)

ABSTRACT. Lightning and fire characteristics within the Northwest Territories (NWT) jurisdiction of the Mackenzie Basin between 1994 and 1999 are examined using data from the lightning detection network operating in the NWT and from the national Large Fire Database maintained by the Canadian Forest Service. The convective storm season with associated lightning activity over this region is short but intense, with a strong peak in cloud-to-ground lightning during July. The maximum area of lightning activity is influenced by local moisture sources and by topography. The diurnal distribution of cloud-to-ground flashes indicates that most of the lightning was linked to thunderstorms initiated by daytime heating. The lightning-initiated fire occurrences peaked during July, while much of the burned area was produced in June. The longer, warmer, and drier summer seasons projected to result from climate change are expected to increase the frequency and intensity of forest fires by the end of the 21st century. Their considerable consequences for forests and wildlife make these changes a concern for northern communities, forest managers, and wildlife biologists.

Key words: lightning, thunderstorms, forest fires, climate change, Northwest Territories

RÉSUMÉ. Les caractéristiques des éclairs et des incendies enregistrés dans le bassin du Mackenzie entre 1994 et 1999 sont examinées à la lumière de données obtenues à partir du réseau de détection des éclairs des Territoires du Nord-Ouest et de la Base de données sur les gros incendies du Service canadien des forêts. Dans cette région, la saison des orages de convection et les éclairs qui en découlent est courte, mais intense, les éclairs nuages-sol atteignant leur point le plus élevé en juillet. L'aire maximale visée par les éclairs est influencée par les sources d'humidité et la topographie locales. La répartition diurne d'éclairs nuages-sol indique que la plupart des éclairs provenaient des orages attribuables à la chaleur de la journée. Les incendies découlant d'éclairs ont atteint leur point culminant en juillet, tandis que la plupart des régions brûlées l'ont été en juin. Les étés plus longs, plus chauds et plus secs susceptibles de résulter des changements climatiques devraient augmenter la fréquence et l'intensité des feux de forêt d'ici la fin du XXI[e] siècle. Leurs répercussions considérables sur les forêts et sur la faune sont une source de préoccupation pour les collectivités du Nord, les experts forestiers et les biologistes de la faune.

Mots clés : éclairs, orages, feux de forêt, changement climatique, Territoires du Nord-Ouest

Traduit pour la revue *Arctic* par Nicole Giguère.

INTRODUCTION

Lightning represents one of the most spectacular displays in the atmosphere and is most commonly produced in summer convective thunderstorms. The Mackenzie GEWEX (Global Energy and Water Cycle Experiment) Study (MAGS) is a multidisciplinary program focused on improving our understanding and prediction of the energy and water cycle of the Mackenzie River Basin (Stewart et al., 1998). MAGS represents the Canadian contribution to the international GEWEX effort (Chahine, 1992a, b). Thunderstorms play an important role in the cycling of water and energy over the boreal ecosystem of the Northwest Territories (NWT). Convective storm systems are a common feature during the summer months, and they account for about half of the annual precipitation (Stewart et al., 1998). Many of these weather systems are also associated with lightning. Using data from the NWT lightning detection network operating in 1994 and 1995, Kochtubajda et al. (2002) reported that cloud-to-ground lightning flashes (indicating the presence of thunderstorms) were detected somewhere within the region on 85% of the days during the summer months. However, there is considerable variation from year to year. Global distributions of lightning

[1] Environment Canada, Meteorological Service of Canada, Hydrometeorology and Arctic Lab, Prairie and Northern Region, Room 200, 4999 98th Avenue, Edmonton, Alberta T6B 2X3, Canada
[2] Corresponding author: bob.kochtubajda@ec.gc.ca
[3] Canadian Forest Service, Great Lakes Forest Research Centre, 1219 Queen Street East, Sault St. Marie, Ontario P6A 2E5, Canada
[4] McGill University, Department of Atmospheric and Oceanic Sciences, 805 Sherbrooke Street West, Montreal, Quebec H3A 2K6, Canada
[5] Golder Associates, 10th floor, 940 – 6th Avenue SW, Calgary, Alberta T2P 3T1, Canada

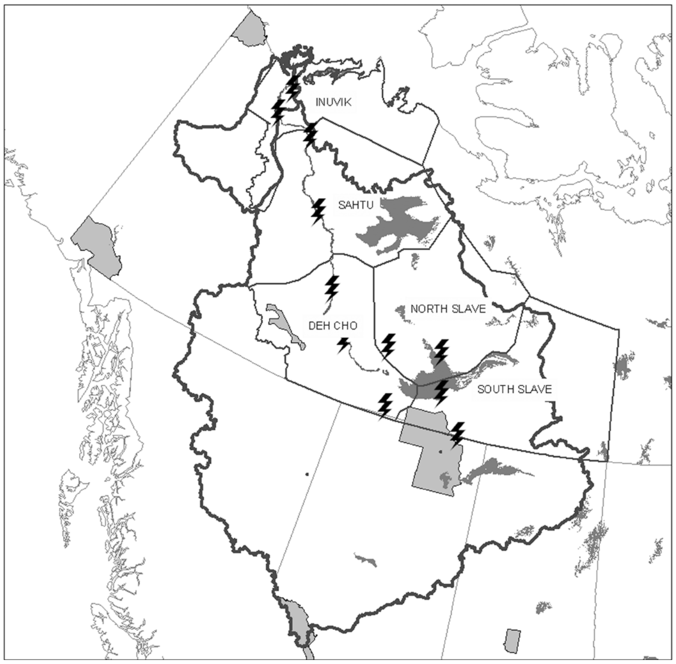


FIG. 1. Map of the study area, showing the NWT fire regions and the configuration of the lightning detection network in 1999.

derived from satellite observations indicate that this region experiences a relatively large amount of lightning, given its high-latitude location (Christian et al., 2003).

Fires are an important disturbance in the NWT: they control diseases and insects, shape landscape diversity, and maintain biological diversity, but they also threaten human life, property, and valuable commercial resources (Ward and Mawdsley, 2000). Various techniques have been used to deduce fire history. Sediment cores extracted from Subarctic lakes in the Great Bear Lake region have shown that fires burned nearly eight thousand years ago (Janzen, 1990; Bastedo, 1998). Bothwell et al. (2004) used tree ring techniques and fire scar analysis to determine fire histories in the Nahanni National Park and the Mackenzie Bison Sanctuary of the NWT, which indicate that fires have been common in these regions as well.

Concern is mounting about the vulnerability of the Canadian Arctic to climate change (Cohen, 1997). There is increasing evidence that current trends in greenhouse gas concentrations will result in a global warming of several degrees Celsius by the middle of the 21st century (Houghton et al., 2001), and this warming will have major impacts in Arctic regions (Watson et al., 1998; Weller and Lange, 1999; ACIA, 2005). Climate model studies suggest that increases in thunderstorm activity are a possible outcome of global warming (Price and Rind, 1994). One possible impact of this increased thunderstorm activity is an increase in the frequency and severity of lightning-initiated forest fires over the boreal regions of northern Alberta, the NWT, and the Yukon.

Lightning sensors installed at various locations throughout the forested area are an important part of the NWT forest fire management program (Ward and Mawdsley, 2000). The widespread, continuous coverage of the lightning detection network provides information that can be used to understand thunderstorm behaviour, which includes determining typical and unusual lightning patterns over this region and gaining an understanding of the processes responsible for them.

The objectives of this study are a) to describe the nature of lightning and convective activity over this high-latitude region by examining their spatial and temporal distributions and their relation to forest fires; and b) to examine the impact of long-term climate warming on the length of the fire season and the seasonal severity rating (SSR) in the region.

STUDY AREA

The Mackenzie River is the largest North American source of freshwater for the Arctic Ocean, ranking 10th in the world by drainage area. The drainage basin covers about 1.8 million km^2, or about 20% of Canada's landmass, and encompasses six provincial, territorial, and federal fire management jurisdictions (Fig. 1) in Canada. Fire management for the Nahanni and the Wood Buffalo National Parks is the federal responsibility of Parks Canada. Within the NWT (which occupies 47% of the basin), the fire management program is divided into five fire regions: the Inuvik, Sahtu, Deh Cho, North Slave, and South Slave (Fig. 1).

Major topographic features in the study area include the Mackenzie Mountains west of the Mackenzie River and Great Bear Lake and Great Slave Lake east of the river. The eastern region of the NWT lies within the Canadian Shield, whereas the area in the north is Arctic tundra. The forested region of the NWT covers approximately 615 000 km^2 (or 18% of the territory) and is largely made up of black spruce (*Picea mariana*), lodgepole pine (*Pinus contorta*), jack pine (*Pinus banksiana*) and trembling aspen (*Populus tremuloides*) tree species, as described by Rowe (1972). Numerous small lakes and marsh areas characterize the landscape.

The regional climate is influenced by several factors, including latitude, amount of incoming solar radiation, topography, and the character of its weather systems (Phillips, 1990). Although incoming solar energy arrives at low angles, which limits the amount of surface warming, increased length of day balances this limitation in the summer (Phillips, 1990). In Yellowknife, for example, daily sunlight lasts about 20 h in June, while at Inuvik the sun does not set in midsummer. In summer, average monthly maximum temperatures are about 20˚C; however, daily temperatures can reach well above 30˚C. Annual precipitation totals over the NWT vary from 200 mm in the northeast to 500 mm in the southwest, and at least half of this precipitation falls during the summer (Stewart et al., 1998).

DATA AND METHODS

Our study used a variety of observational data sources and model-derived products. In particular, we used the archived cloud-to-ground lightning flash and fire data from the NWT government and the fire data from the Canadian Forest Service's national Large Fire Database (Stocks et al., 2002). The period 1994–99 was selected because the area burned showed great variability and the lightning network was most reliable and relatively stable. This study period could also serve as an analogue for future climate change.

Daily lightning flash statistics were determined from the lightning detection network operating in the NWT. The network underwent a few configuration changes between 1994 and 1999, including the reactivation of one direction-finding (DF) station in the Inuvik region and the relocation of three DF stations in the North Slave, South Slave, and Sahtu regions (Fig. 1). The resulting uncertainties in the location accuracy of the lightning data and the detection efficiency of the network are described in Kochtubajda et al. (2002). Expected error range is 3–10 km within the highest density region of the network and 12–22 km at its periphery, with an overall detection efficiency of about 70%.

The Large Fire Database (LFDB; Stocks et al., 2002) was also used in this study. This data set, which comprises forest fire information from all Canadian agencies, including provinces, territories, and Parks Canada, contains only fires greater than 200 ha in size. Although few in number, these large fires account for approximately 97% of the total area burned (Stocks et al., 2002).

Daily data were obtained from two climate models at two time periods, one corresponding to the present and the other corresponding to a future scenario. The two General Circulation Models (GCMs) were from the Canadian Centre for Climate Modelling and Analysis (CCCma) and the Hadley Centre for Climate Prediction and Research (United Kingdom). The CCCma model (Flato et al., 2000) used the range 1975–95 to correspond to a $1 \times CO_2$ scenario, while the Hadley model used the range 1975–90. The CCCma model used was the First Generation Coupled GCM (CGCM1). This model included both greenhouse gas and sulphate aerosol forcing, with the CO_2 increasing by 1% per year. At this rate, the time period 2080–2100 corresponded roughly to a $3 \times CO_2$ scenario. The Hadley model (Gordon et al., 2000), HadCM3GGa1, contained only greenhouse gas forcing and output 2080–99 as its $3 \times CO_2$ scenario. The grid for the Hadley model had slightly higher resolution at 3.75˚ longitude by 2.5˚ latitude (vs. 3.75˚ by 3.75˚ for CCCma). All analyses (except fire season length) were performed for a fire season of May 01 to August 31. Fire season length was determined using data for April 1 to September 30. The GCM outputs of temperature, precipitation amount, and relative humidity data were adjusted using correction factors derived from a comparison between the $1 \times CO_2$ simulation and observed data (Flannigan et al., 2005).

We used the adjusted daily output from the two GCMs to generate the six standard indices (FFMC, DMC, DC, ISI, BUI, and FWI, defined below) that account for the effects of fuel moisture and wind on fire behaviour in the Fire Weather Index (FWI) System (Van Wagner, 1987). The weather-based FWI System models fuel moisture using a dynamic bookkeeping method that tracks the drying and wetting of distinct fuel layers in the forest floor. The moisture content of these layers is represented by three codes: FFMC (Fine Fuel Moisture Content) for fine fuels, DMC (Duff Moisture Code) for loosely compacted organic material, and DC (Drought Code) for a deep layer of compact organic material. Drying time lags for these three fuel layers, under normal conditions (temperature 21.1˚C, relative humidity 45%), are two-thirds of a day (FFMC), 15 days (DMC), and 52 days (DC). These moisture indexes are combined to create a generalized index of the availability of fuel for consumption (Build Up Index, BUI) and the FFMC is combined with wind to estimate the potential spread rate of a fire (Initial Spread Index, ISI). The BUI and ISI are combined to create the FWI, which is an estimate of the potential intensity of a spreading fire.

From the FWI, we calculated the seasonal severity rating (SSR), a seasonal average (May to August) representing fire control difficulty (Van Wagner, 1970), for each time period and model. We also determined the ratio of the $3 \times CO_2$ to the $1 \times CO_2$ scenario of mean SSR. To calculate fire season length, we used a temperature-duration criterion to determine the start and the end of the fire season. The start was considered to be the first three consecutive days whose maximum daily temperatures averaged more than 3.5˚C. The end of the fire season was defined as the first time after August 1 that the three-day average of maximum temperatures dropped below 3.5˚C.

WEATHER SUMMARY FOR 1994–99

During the period 1994–99, the Mackenzie Basin experienced considerable changes to its climate. Cao et al. (2002), Louie et al. (2002), and Stewart et al. (2002), who described various aspects of the climate during 1994 and 1995, found that the summer of 1994 and the spring and summer of 1995 were drier than normal. Some results of these dry conditions were record low surface-humidity values during the summer of 1995, above-normal cloud-base heights, below-normal precipitation, and some of the lightest surface winds on record.

The warmest year ever recorded—globally, nationally, and regionally—was 1998. For Canada, mean temperatures were 2.5˚C warmer than normal, and in terms of total precipitation, 1998 was the ninth driest year in the 51 years since comparable nationwide temperature records began in 1948. In the Mackenzie Basin, annual mean temperatures were 3.9˚C above normal. In terms of the precipitation regime, the western and southern areas of the basin were slightly drier than normal, whereas the eastern area

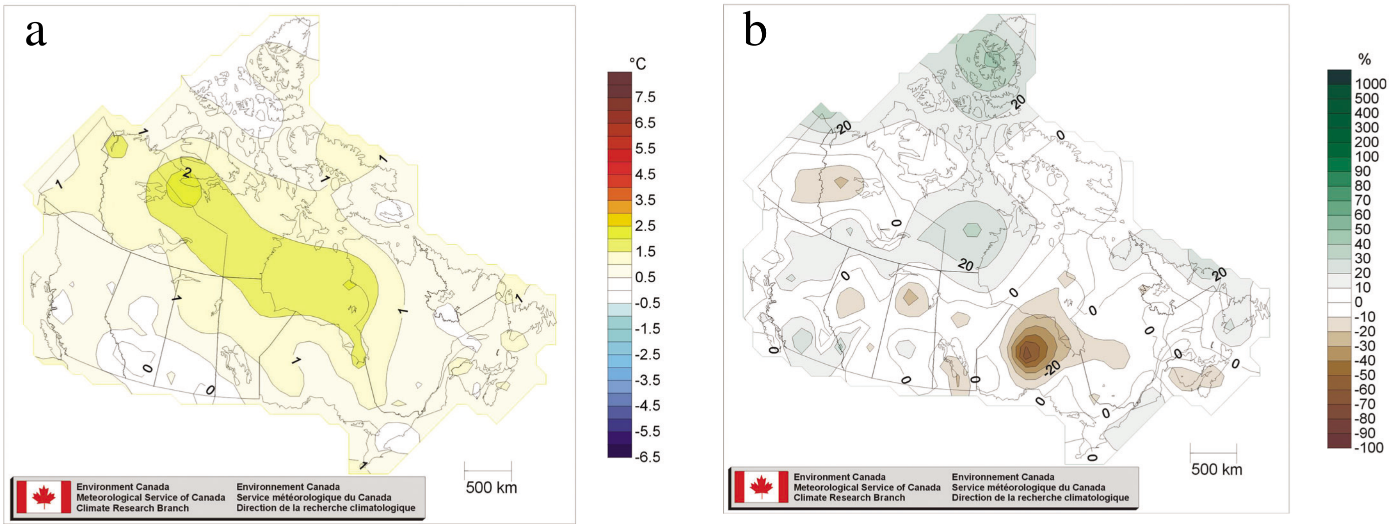
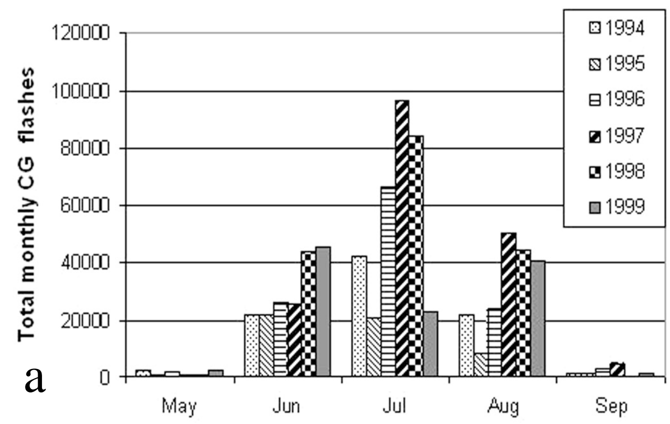


FIG. 2. Composite maps for the summers of 1994 to 1999, depicting departures in (a) temperature and (b) precipitation from the 1951–80 climatology in Canada.



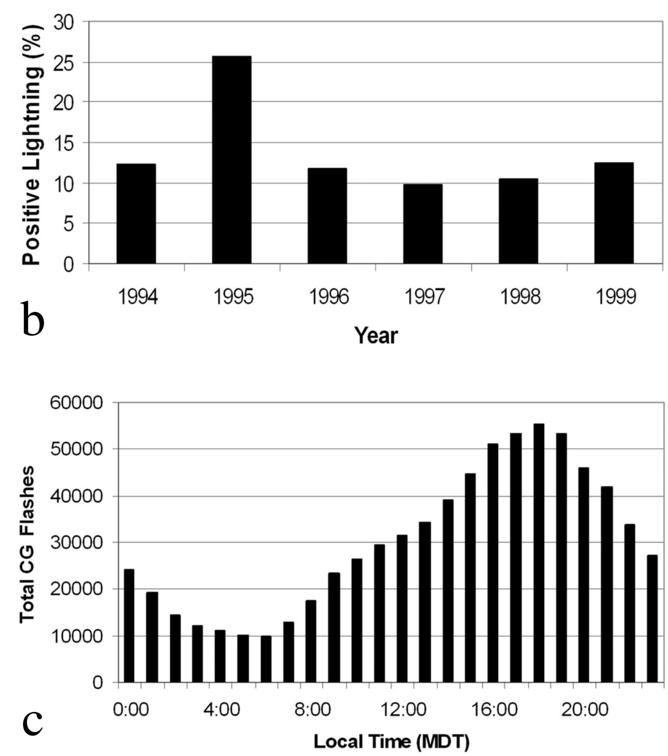


FIG. 3. Selected characteristics of cloud-to-ground lightning in the NWT, 1994–99. a) The monthly distribution of lightning flashes. b) The annual fraction of positive lightning flashes. c) The diurnal distribution of lightning flashes.

was slightly wetter than normal, and the year was the 21st driest on record.

A composite map of temperature departures (Fig. 2a) shows that summer temperatures during the 1994–99 study period were 1.0–1.5˚C warmer than the 1951–80 climatology over the NWT. From a precipitation perspective, the Sahtu region was slightly drier than normal, whereas the extreme northwest portion of the Inuvik region and the southern portions of the Deh Cho and South Slave regions were slightly wetter than normal (Fig. 2b).

LIGHTNING AND FOREST FIRE ACTIVITY FOR 1994–99

Lightning Summary

From 1994 to 1999, over 709 000 cloud-to-ground lightning flashes were recorded within the study area. The distribution of lightning activity over the summer months is illustrated in Figure 3a. The lightning season is short but intense, peaking in July and diminishing by August. Convective activity is rare in September. The start of the lightning season is influenced by the timing of snowmelt on the land cover, while the southward passage of the Arctic cold front in late summer usually ends the convective season.

Positive lightning flashes (lightning discharges that transfer a positive charge to the earth) typically account for about 10% of all the cloud-to-ground flashes around the world (Latham and Williams, 2001). During the study period, the fraction of positive flashes over the NWT comprised approximately 12% of all the ground flashes (Fig. 3b). Lightning activity during the 1995 fire season, however, was very unusual. The thunderstorms produced

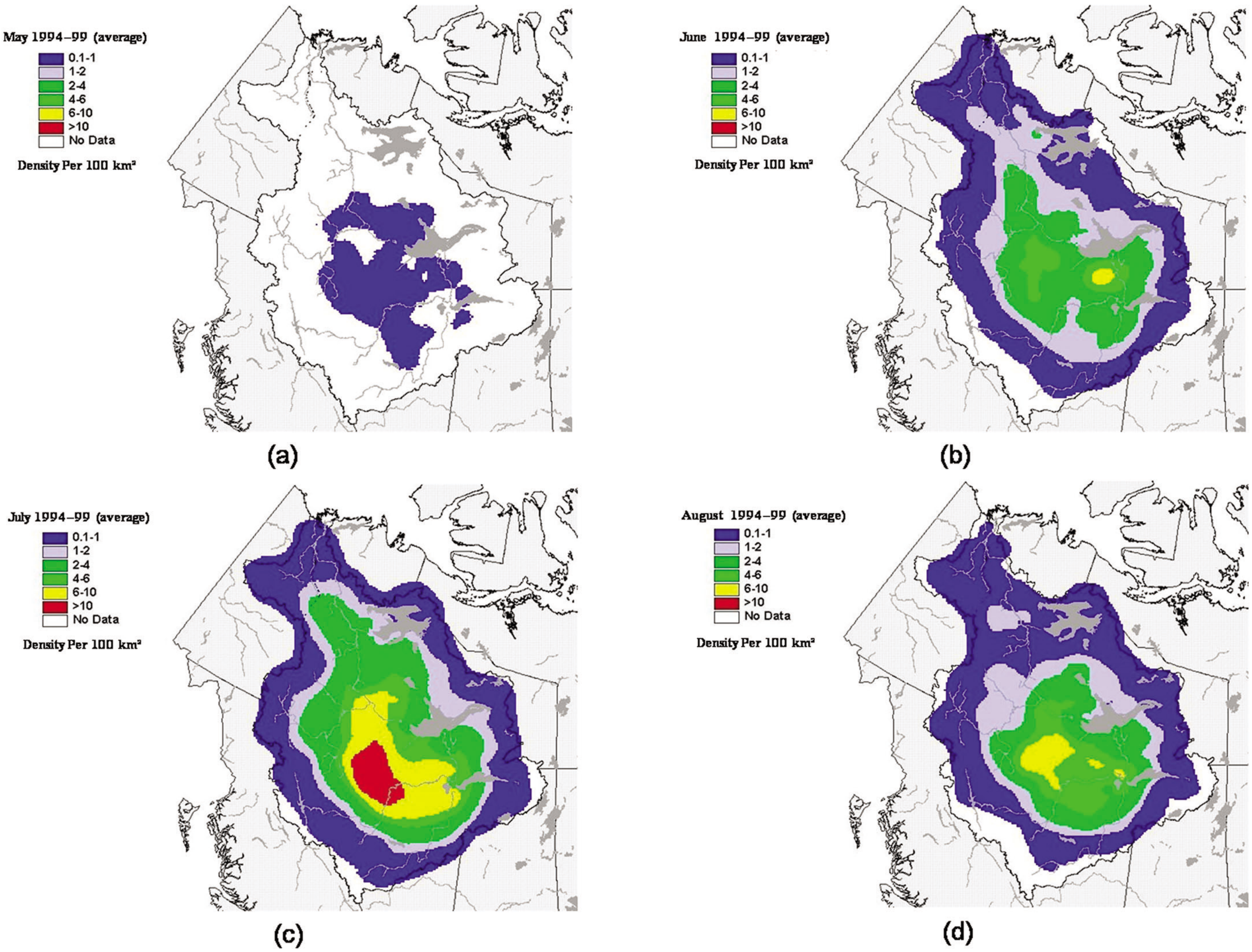


FIG. 4. The monthly spatial distribution of lightning activity (strikes/100 km^2) averaged over the period 1994–99 for a) May, b) June, c) July, and d) August.

a relatively low amount of lightning (approximately 53% below the seasonal average of 118 K flashes), but an unusually high fraction of positive flashes (approximately 25%). A status check found the detection network to be completely operational (B. Croft, pers. comm. 2004). Surface weather observations and satellite imagery suggest that the smoke from existing forest fires may have contributed to the higher level of positive lightning activity (Kochtubajda et al., 2002).

The diurnal variations of lightning during this period (Fig. 3c) show that the majority of flashes occur in the mid-afternoon, peaking near 1800 local time. This information indicates that air-mass thunderstorms generated by daytime heating (Kochtubajda et al., 2002), as opposed to longer-lived convective complexes that last through the night, continue to produce the bulk of the lightning.

Lightning activity patterns during this study period (Fig. 4) illustrate seasonal and spatial variability. In the early part of the season, the region of lightning activity (densities up to 1 flash/100 km^2) extends from Fort Smith in the south Slave region westward to Fort Simpson in the Deh Cho region, as well as southward into the Peace-Athabasca region of Alberta. Lightning densities intensify to 2–4 flashes/km^2 through the Sahtu region in July, and by August, the activity lessens progressively going south-east from the Sahtu region into the North Slave region. The maximum area of lightning activity extends from the wetlands region through the Cameron Hills of the NWT to the Clear Hills of the Peace River Basin in northern Alberta.

Forest Fire Summary

The fire regime of the NWT can be described by the intensity, frequency, seasonality, size, type, and severity of the fires (Weber and Flannigan, 1997). The fire season typically starts in late May and usually ends by early September (Forster, 1995). Cloud-to-ground lightning flashes associated with summer thunderstorms typically start approximately 80% of the forest fires in the NWT (Epp and Lanoville, 1996). Over the past 30 years, on average, 320 fires have occurred each year in the NWT, and these fires have consumed approximately 675 000 ha

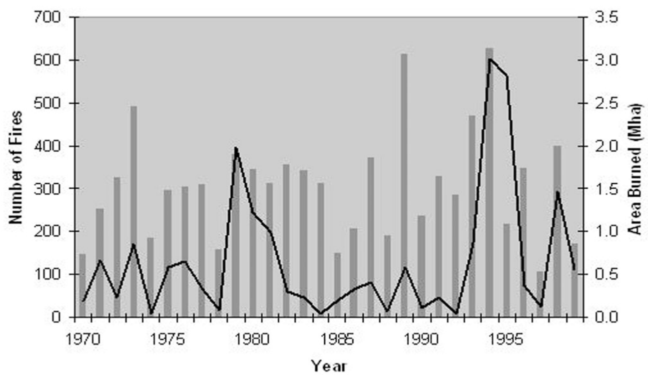


FIG. 5. Annual variation in the number of fires (bars) and forest area burned (solid line) in the NWT from 1970 to 1999.

(Ward and Mawdsley, 2000). The number of fires and the area burned are highly variable from year to year (Fig. 5). The lowest number of fires in any year occurred during the 1997 fire season when only 105 fires were started, whereas the highest number of fires (627) occurred in 1994 (National Forestry Database). The spatial distribution of fires (Fig. 6) shows that most of the territory has experienced fires at some time.

The 1994–99 fire seasons included some of the most severe forest fires experienced in the NWT. A total of 1695 lightning-initiated fires burned approximately 8.3 Mha, or 13.5% of the available forest. Only 22% of the fires were larger than 200 ha, but these fires accounted for more than 98% of the total area consumed. Unusually large areas burned in two of these years, over 3 Mha in 1994 and about 2.8 Mha in 1995. In fact, 1994–95 was the worst two-year period on record for area burned in Canada (Simard, 1997). Area-burned statistics are influenced by a number of factors, including the weather, forest extent, topography, composition of the landscape, fire suppression policies and priorities, organizational size and efficiency, and fire site accessibility.

The Percent Annual Area Burned (PAAB) can be used to represent the frequency of large fires over a defined area, such as an ecozone or ecoregion (Stocks et al., 2002). In the combined areas of the Taiga Plains and Taiga Shield West ecozones, Stocks et al. show that an average of 0.73% of the land area has burned annually over the 39 years of record. We calculated a PAAB value of 2.21% over the forested area of the NWT for 1994–99. Our study period thus reflects an unusually active period of fire.

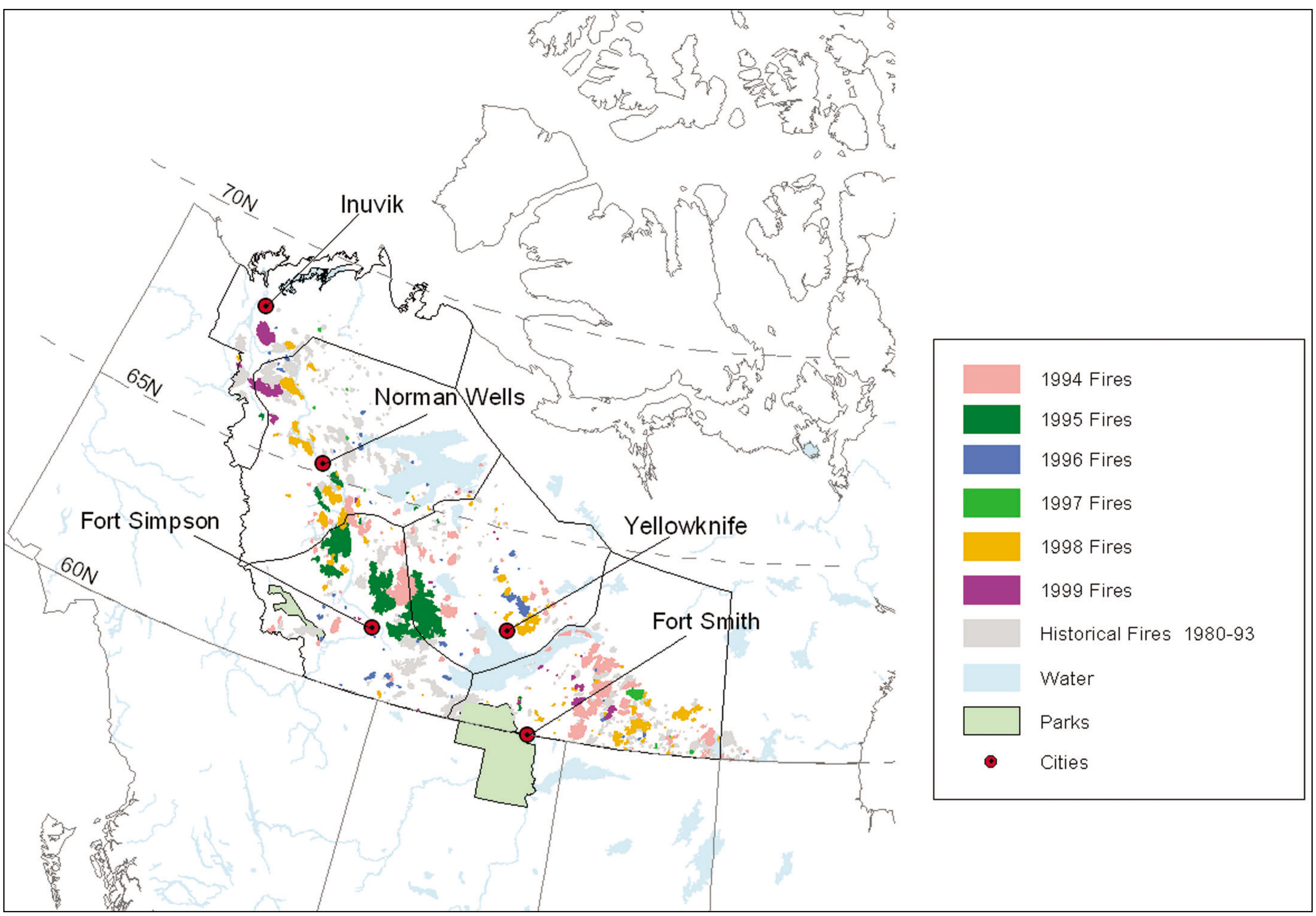


FIG. 6. Map depicting the forest fire history in the NWT from 1980 to 1999.

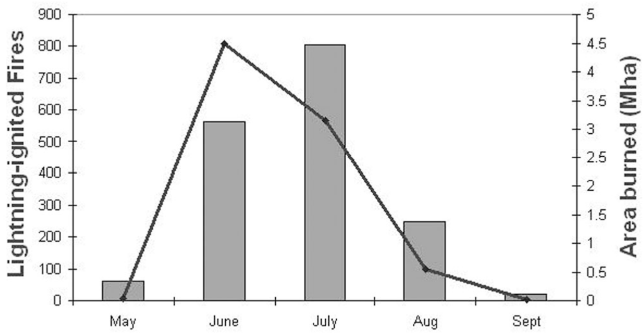


FIG. 7. Monthly fire occurrence (bars) and area burned (line) for the period 1994–99.

The temporal pattern of lightning-ignited fire occurrence and area burned by lightning is unusual, in that fire occurrences peak in July, while area burned is greatest in June (Fig. 7). Information for 1959–99 from the Large Fire Database (Stocks et al., 2002) also shows that most of the area burned occurs in June (~40%), with slightly less in July (33%). Several possible reasons why this pattern occurs are that the minimal moisture content of conifer needles in spring may give rise to increased fire activity (Van Wagner, 1967); June is normally drier than July; and winds are typically stronger in June (Phillips, 1990).

CLIMATE CHANGE

Climate change is expected to have significant impact on the North. Recently, the National Academy of Sciences in the United States identified the Arctic and Subarctic regions as being especially vulnerable to abrupt climate change because of their sensitivity to changes in temperature, water-table levels, and frequency of fires (National Academy of Sciences, 2002). Testimonials given at the Impacts and Adaptation workshop in Yellowknife demonstrate the concerns of Northerners about climate change and its impact on their traditional lifestyle (GeoNorth, 2000). For example, Inuvialuit elders have observed an increase in extreme weather since the 1950s, with more thunder and lightning on Banks Island, while Gwich'in elders have noticed warmer weather, more variable weather patterns, and more forest fires (GeoNorth, 2000).

Future Climate and Fire

Figure 8 shows the ratio of 3 × CO_2 to 1 × CO_2 mean seasonal severity rating as predicted by the CCCma and Hadley models. Although both models suggest significant increases in SSR (CCCma: 1.19; Hadley: 1.44) averaged over the Mackenzie Basin, they differ in the details. The CCCma model suggests little change in SSR over the southern Mackenzie region of the NWT, but significant increases in northwestern NWT. The Hadley model, on the other hand, suggests significant increases in the southern NWT and northern Alberta and British Columbia, but decreasing SSR over northwestern NWT. This shows that there is a great deal of regional variation in the response to climate change. Some of these differences arise because the models differ in their large-scale scenario patterns. In addition, the coarse spatial resolution of the GCM (ca. 400 km) lowers confidence in its results over complex, mountainous terrain in part of our study region. In such areas, it is better to use a regional climate model (RCM) with finer spatial resolution (ca. 40 km; Caya and Laprise, 1999) that can better resolve the terrain.

Flannigan and Van Wagner (1991) compared seasonal fire severity rating values (SSR) of a 2 × CO_2 (mid-21st century) scenario and the 1 × CO_2 (1975–90s) scenario across Canada. The study used monthly anomalies from three GCMs: Geophysical Fluid Dynamics Laboratory (GFDL), Goddard Institute for Space Studies (GISS), and Oregon State University (OSU). Their results suggest increases in the SSR all across Canada and an average increase of nearly 50%, which would translate into ca. 50% increase in area burned. Stocks et al. (1998) used monthly data from four GCMs to examine climate change and forest fire potential in Russian and Canadian boreal forests. Forecast seasonal fire weather severity under a 2 × CO_2 scenario was similar for the four GCMs, indicating large increases in the areal extent of extreme fire danger in both countries. Stocks et al. (1998) also performed a monthly analysis using the Canadian GCM. For both Canada and Russia, it showed an earlier start to the fire season, as well as significant increases in the area experiencing high to extreme fire danger, particularly during June and July.

Other factors such as ignition agents, length of the fire season, and fire management policies can greatly influence the impact of climate change on the fire regime. Ignition probabilities may increase in a warming world because of increased cloud-to-ground lightning discharges. Price and Rind (1994) suggest that lightning-caused fires will increase by 44% (and the associated area burned, by 78%) by the end of the 21st century. They assume no changes in fuels, which can greatly influence the lightning ignitions and area burned. The longer fire season will begin earlier in the spring and extend longer into the autumn.

Figure 9 shows changes in fire season length from 1 × CO_2 to 3 × CO_2 over our region of interest, as predicted by the CCCma and Hadley GCMs. Both models indicate an extension of 30–50 days in the fire season length over much of the Mackenzie Basin. These estimates may be conservative because the analysis of fire season length was constrained by our criteria and time period. It is possible that in some situations we ended the fire season prematurely (e.g., if a cold snap occurred early in September but the rest of the month was relatively warm). According to our temperature-duration criterion, the fire season would have ended, though in reality the fires may have continued.

Wotton and Flannigan (1993) estimated that on average, fire season length in Canada will increase by 22%, or 30 days,

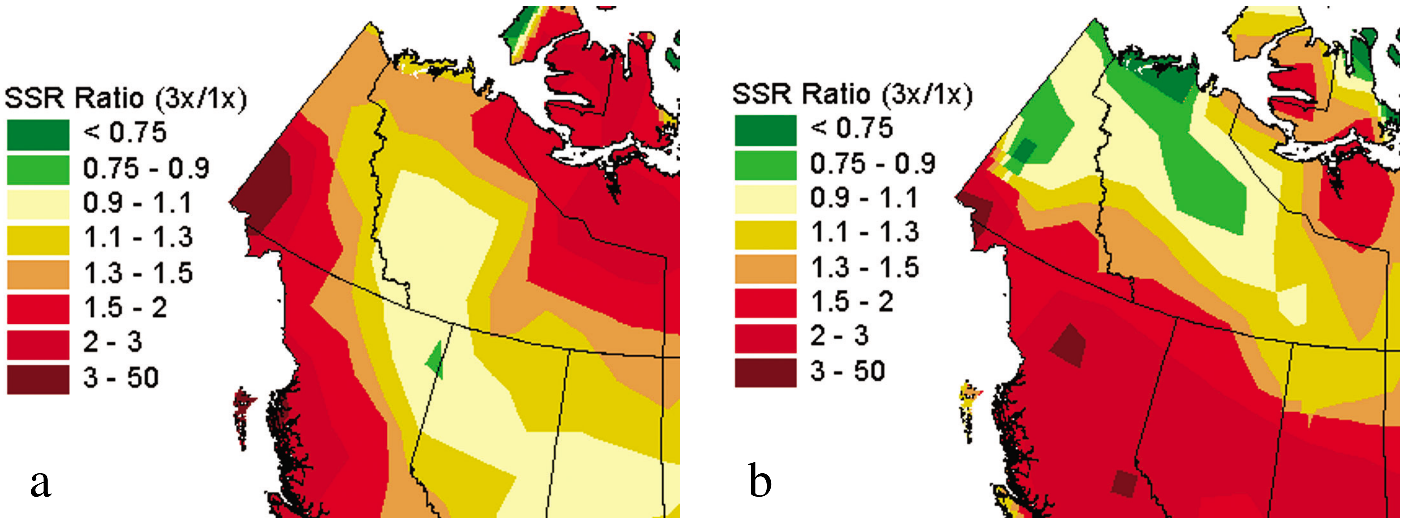


FIG. 8. Projected changes in the ratio of $3 \times CO_2$ to $1 \times CO_2$ mean seasonal fire severity from the GCMs of (a) the Canadian Climate Centre and (b) the Hadley Centre. Red indicates increases, while yellow indicates little or no change.

in a $2 \times CO_2$ world. Fire management policies and effectiveness will continue to change. Also, research has suggested that the persistence of blocking ridges in the upper atmosphere will increase in a $2 \times CO_2$ climate (Lupo et al., 1997). This change could have a significant impact on forest fires, as these upper ridges are associated with dry and warm conditions at the surface that are conducive to forest fires. All these confounding effects can dampen or amplify the impact of a changing climate on the fire regime.

Vulnerability

How vulnerable are our northern ecosystems and communities to changes in the fire regime? Our results suggest that the fire season will be longer and fire activity will increase. A significantly larger area burned in the NWT would have important implications for forests, forestry activities, community protection and carbon budgets. For example, emissions of carbon dioxide from forest fires over the past 40 years are already equivalent, on average, to 20% of fossil fuel emissions in Canada (Amiro et al., 2001). Fire management agencies in Canada already spend half a billion dollars a year on direct suppression costs, and these costs could rise significantly. Additionally, communities and other valuables such as timber, traplines, and recreational areas could be at a higher risk of forest fires in the future.

The interplay between climate change and area burned could overshadow the direct effects of global warming on the distribution and migration of plant species (Weber and Flannigan, 1997). If fires become too frequent, many tree species will not reach sexual maturity and thus will not be able to regenerate after fire. In such cases, we could see the boreal forest giving way to aspen parkland, and if fire continues to be frequent, the aspen parkland may eventually give way to grassland. The southern edge of the boreal forest may shift northward rapidly because of drought, disease, and especially fire, but soil and nutrient constraints will slow the northward advance of the forest's northern edge. The end result may be a decrease in forested area in the Mackenzie Basin. Decreased forested area in the basin would have impacts on the hydrology and climate of the region through various feedbacks like reduced surface vegetation cover and changed albedo (Bonan, 2002). All these factors suggest that the northern forests and communities may be even more susceptible to forest fires in the future and face the possibility of some significant and rapid changes.

CONCLUSIONS

Our study of the fire regime of the Northwest Territories jurisdiction of the Mackenzie Basin between 1994 and 1999 used data from the lightning detection network operating in the NWT and fire data from the Canadian Forest Service's national Large Fire Database. The convective storm season and associated lightning activity are short but intense, with a strong peak in cloud-to-ground lightning during June and July. The maximum area of lightning activity is influenced by local moisture sources and by topography. The diurnal distribution of cloud-to-ground flashes indicates that most of the lightning is linked with thunderstorms initiated by daytime heating. The lightning-initiated fire occurrences peaked during July, although much of the burned area occurred in June.

Scenario information extending to near the end of the 21st century indicates that the boreal forest ecosystem will be severely affected by the projected changes in temperature, precipitation, and fire regimes resulting from climate change. The regional movement toward longer, warmer, and drier seasons resulting from global climate change is expected to increase the vulnerability of forested areas to fires. A key outstanding issue for future studies is better

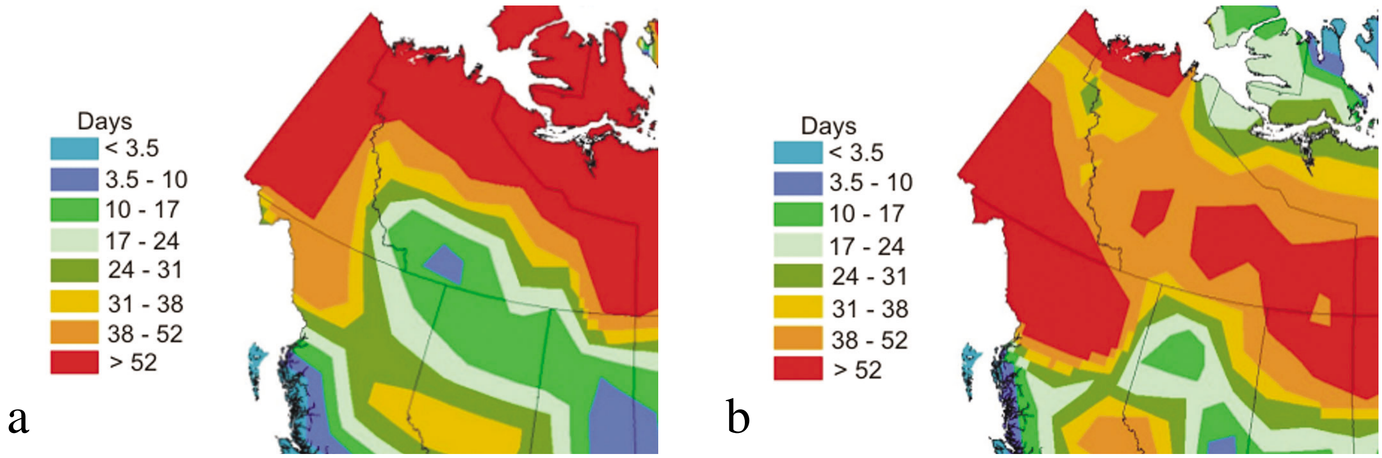


FIG. 9. Changes in fire-season length from 1 × CO_2 to 3 × CO_2 as projected by the GCMs of (a) the Canadian Climate Centre and (b) the Hadley Centre. Values in orange and red represent increases of more than 31 days.

understanding of the degree to which frequency and characteristics of lightning will change over this region. Nonetheless, given an increasingly vulnerable forest, the ramifications of future increases in forest fires are of considerable concern to northern residents, forest managers, and wildlife biologists.

ACKNOWLEDGEMENTS

Funding support for this study was provided by the Prairie and Northern Region of Environment Canada, the Natural Sciences and Engineering Research Council of Canada, and the Northern Ecosystem Initiative. We are grateful to Bob Whitewood from the Climate Research Branch of the Meteorological Service of Canada for his assistance in preparing Figure 2, to Monique Lapalme of the Hydrometeorology and Arctic Lab for preparing Figures 1, 3, 4, 5, and 7, and to Rick Lanoville from the Forest Management Division of the Government of the Northwest Territories in Fort Smith for providing the lightning data. Mark Heathcott of Parks Canada provided the fire history data for Wood Buffalo National Park, while Steve Catto of Parks Canada and Pete Bothwell of the Canadian Forest Service provided the fire history data for Nahanni National Park. The historical forest fire statistics depicted in Figure 5 were obtained from the National Forestry Database, Canadian Council of Forest Ministers (http://nfdp.ccfm.org/). We also thank the three anonymous reviewers for their useful suggestions, which led to an improved version of the manuscript.

REFERENCES

ACIA (ARCTIC CLIMATE IMPACT ASSESSMENT). 2005. Arctic climate impact assessment: Scientific report. Cambridge: Cambridge University Press. 1042 p.

AMIRO, B.D., TODD, J.B., WOTTON, B.M., LOGAN, K.A., FLANNIGAN, M.D., STOCKS, B.J., MASON, J.A., SKINNER, W.R., MARTELL, D.L., and HIRSCH, K.G. 2001. Direct carbon emissions from Canadian forest fires, 1959 to 1999. Canadian Journal of Forest Research 31:512–525.

BASTEDO, J. 1998. Reaching North: A celebration of the Subarctic. Red Deer, Alberta: Red Deer College Press. 255 p.

BONAN, G.B. 2002. Ecological climatology: Concepts and applications. Cambridge: Cambridge University Press. 678 p.

BOTHWELL, P.M., de GROOT, W.J., DUBÉ, D.E., CHOWNS, T., CARLSSON, D.H., and STEFNER, C.N. 2004. Fire regimes in Nahanni National Park and the Mackenzie Bison Sanctuary, Northwest Territories, Canada. In: Engstrom, R.T., and de Groot, W.J., eds. Proceedings of the 22nd Tall Timbers Fire Ecology Conference: Fire in temperate, boreal and montane ecosystems. Tallahassee, Florida: Tall Timbers Research Station. 43–54.

CAO, Z., WANG, M., PROCTOR, B.P., STRONG, G.S., STEWART, R.E., RITCHIE, H., and BURFORD, J. 2002. On the physical processes associated with the water budget and discharge of the Mackenzie basin during the 1994/95 water year. Atmosphere-Ocean 40:125–143.

CAYA, D., and LAPRISE, R. 1999. A semi-implicit semi-lagrangian regional climate model: The Canadian RCM. Monthly Weather Review 127(3):341–362.

CHAHINE, M.T. 1992a. GEWEX: The global energy and water cycle experiment. Eos Transactions 73(2):9.

———. 1992b. The hydrological cycle and its influence on climate. Nature 359:373–380.

CHRISTIAN, H.J., BLAKESLEE, R.J., BOCCIPPIO, D.J., BOECK, W.J., BUECHLER, D.E., DRISCOLL, K.T., GOODMAN, S.J., HALL, J.M., KOSHAK, W.J., MACH, D.M., and STEWART, M.F. 2003. Global frequency and distribution of lightning as observed from space by the Optical Transient Detector. Journal of Geophysical Research 108 (D1), 4005, doi: 10.1029/2002JD002347.

COHEN, S.J. 1997. What if and so what in Northwest Canada: Could climate change make a difference to the future of the Mackenzie Basin? Arctic 50(4):293–307.

EPP, H., and LANOVILLE, R. 1996. Satellite data and geographic information systems for fire and resource management in the Canadian Arctic. Geocarto International 11:97–103.

FLANNIGAN, M.D., and VAN WAGNER, C.E. 1991. Climate change and wildfire in Canada. Canadian Journal of Forest Research 21:66–72.

FLANNIGAN, M.D., LOGAN, K.A., AMIRO, B.D., SKINNER, W.R., and STOCKS, B.J. 2005. Future area burned in Canada. Climatic Change 72(1–2):1–16. doi: 10.1007/s10584-005-5935-y.

FLATO, G.M., BOER, G.J., LEE, W.G., McFARLANE, N.A., RAMSDEN, D., READER, M.C., and WEAVER, A.J. 2000. The Canadian Centre for Climate Modelling and Analysis Global Coupled Model and its climate. Climate Dynamics 16: 451–467.

FORSTER, W. 1995. Northwest Territories fire weather report. Fort Smith, Northwest Territories: Territorial Forest Fire Centre, GNWT Department of Renewable Resources. 63 p.

GEONORTH LTD. 2000. Climate change impacts and adaptation strategies for Canada's northern territories: Final Workshop Report. 27–29 February 2000, Yellowknife, NWT. Report prepared for Natural Resources Canada and Environment Canada. Available at Environment Canada Library, Suite 301, 5204 – 59th Avenue, Yellowknife, Northwest Territories X1A 1E2. 61 p.

GORDON, C., COOPER, C., SENIOR, C.A., BANKS, H., GREGORY, J.M., JOHNS, T.C., MITCHELL, J.F.B., and WOOD, R.A. 2000. The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. Climate Dynamics 16(2-3): 147–168.

HOUGHTON, J.T., DING, Y., GRIGGS, D.J., NOGUER, M., VAN DER LINDEN, P.J., DAI, X., MASKELL, K., and JOHNSON, C.A., eds. 2001. Climate change 2001: The scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press. Available at http://www.ipcc.ch/pub/online.htm.

JANZEN, S.S. 1990. The burning North: A history of fire and fire protection in the Northwest Territories. MA thesis, University of Alberta, Edmonton, Alberta.

KOCHTUBAJDA, B., STEWART, R.E., GYAKUM, J.R., and FLANNIGAN, M.D. 2002. Summer convection and lightning over the Mackenzie River Basin and their impacts during 1994 and 1995. Atmosphere-Ocean 40:199–220.

LATHAM, D., and WILLIAMS, E. 2001. Lightning and forest fires. In: Johnson, E.A., and Miyanishi, K., eds. Forest fires: Behavior and ecological effects. San Diego: Academic Press. 375–418.

LOUIE, P.Y.T., HOGG, W.D., MACKAY, W.D., ZHANG, X., HOPKINSON, R.F., and SOULIS, E.D. 2002. The water balance climatology of the Mackenzie basin with reference to the 1994/95 water year. Atmosphere-Ocean 40:159–180.

LUPO, A.R., OGLESBY, R.J., and MOKHOV I.I. 1997. Climatological features of blocking anticyclones: A study of Northern Hemisphere CCM1 model blocking events in present-day and double CO_2 concentration atmosphere. Climate Dynamics 13:181–195.

NATIONAL ACADEMY OF SCIENCES. 2002. Abrupt climate change: Inevitable surprises. Committee on Abrupt Climate Change, Ocean Studies Board, Polar Research Board, Board on Atmospheric Sciences and Climate, Division on Earth and Life Studies, National Research Council. Washington, D.C.: National Academy Press. 230 p.

PHILLIPS, D. 1990. The climates of Canada. Ottawa: Supply and Services Canada. 176 p.

PRICE, C., and RIND, D. 1994. Possible implications of global climate change on global lightning distributions and frequencies. Journal of Geophysical Research 99:10823–10831.

ROWE, J.S. 1972. Forest regions of Canada. Publication No. 1300. Ottawa: Canadian Forestry Service, Department of Fisheries and the Environment. 172 p.

SIMARD, A.J. 1997. National workshop on wildland fire activity in Canada. Information Report ST-X-13. Ottawa: Science Branch, Canadian Forestry Service, Natural Resources Canada. 38 p.

STEWART, R.E., LEIGHTON, H.G., MARSH, P., MOORE, G.W.K., RITCHIE, H., ROUSE, W.R., SOULIS, E.D., STRONG, G.S., CRAWFORD, R.W., and KOCHTUBAJDA, B. 1998. The Mackenzie GEWEX Study: The water and energy cycles of a major North American river basin. Bulletin of the American Meteorological Society 79:2665–2683.

STEWART, R.E., BUSSIERES, N., CAO, Z., CHO, H.R., HUDAK, D.R., KOCHTUBAJDA, B., LEIGHTON, H., LOUIE, P.Y.T., MACKAY, M.D., MARSH, P., STRONG, G.S., SZETO K.K., and BURFORD, J.E. 2002. Hydrometeorological features of the Mackenzie basin climate system during the 1994/1995 water year: A period of record low discharge. Atmosphere-Ocean 40:257–278.

STOCKS, B.J., FOSBERG, M.A., LYNHAM, T.J., MEARNS, L., WOTTON, B.M., YANG, Q., JIN, J.-Z., LAWRENCE, K., HARTLEY, G.R., MASON, J.A., and McKENNEY, D.W. 1998. Climate change and forest fire potential in Russian and Canadian boreal forests. Climatic Change 38:1–13.

STOCKS, B.J., MASON, J.A., TODD, J.B., BOSCH, E.M., WOTTON, B.M., AMIRO, B.D., FLANNIGAN, M.D., HIRSCH, K.G., LOGAN, K.A., MARTELL, D.L., and SKINNER, W.R. 2002. Large forest fires in Canada, 1959–1997. Journal of Geophysical Research 108 (D1), 8149, doi: 10.1029/2001JD000484.

VAN WAGNER, C.E. 1967. Seasonal variation in moisture content of eastern Canadian tree foliage and the possible effect on crown fires. Forestry Branch Publication 1204. Ottawa: Canada Department of Forests and Rural Development.

———. 1970. Conversion of William's Severity Rating for use with the fire weather system. Information Report PS-X-21. Petawawa, Ontario: Canadian Forest Service, Petawawa Forest Experiment Station.

———. 1987. Development and structure of the Canadian forest fire weather index system. Forestry Technical Report 35. Ottawa: Canadian Forest Service.

WARD, P.C., and MAWDSLEY, W. 2000. Fire management in the boreal forest of Canada. In: Kasischke, E.S., and Stocks, B.J., eds. Fire, climate change and carbon cycling in the boreal forest. New York: Springer-Verlag. 66–84.

WATSON, R.T., ZINYOWERA, M.C., and MOSS, R.H., eds. 1998. The regional impacts of climate change: An assessment of vulnerability. A special report of IPCC Working Group II. New York: Cambridge University Press. 517 p.

WEBER, M.G., and FLANNIGAN, M.D. 1997. Canadian boreal forest ecosystem structure and function in a changing climate: Impact on fire regimes. Environmental Reviews 5:145–166.

WELLER, G., and LANGE, M., eds. 1999. Impacts of global climate change in the Arctic regions. Report from a Workshop on the Impacts of Global Change, Tromsø, Norway. Available from the Center for Global Change and Arctic System Research, University of Alaska, Fairbanks, P.O. Box 757740, Fairbanks, Alaska 99775-7740. 59 p.

WOTTON, B.M., and FLANNIGAN, M.D. 1993. Length of the fire season in a changing climate. Forestry Chronicle 69:187–192.