8.4 THE INFLUENCE OF ATMOSPHERIC INSTABILITY ON FIRE BEHAVIOUR IN THE NORTHWEST TERRITORIES, CANADA

B. Kochtubajda[1] , M.D. Flannigan[2], J. R. Gyakum[3], and R.E. Stewart[4]

[1]Meteorological Service of Canada, Edmonton, Alberta, CANADA
[2]Canadian Forest Service, Edmonton, Alberta, CANADA
[3]McGill University, Montreal, Quebec, CANADA
[4]Meteorological Service of Canada, Downsview, Ontario, CANADA

1. INTRODUCTION

Wildfires pose the greatest danger within the boreal ecosystem for fire managers in the Northwest Territories (NWT). Although they are beneficial to the control of diseases and insects as well as maintaining biological diversity, fires also threaten human life, property and valuable commercial resources. The fire season typically starts in late May and usually ends by early September.

Weather is critical to forest fires. Not only does it affect the ignition of fires through lightning, but it also influences fire behaviour. Strong winds, high temperatures and low humidity enhance the rate of fire growth. Atmospheric instability, another important factor in fire growth, can influence the spread and intensity of wildfires. For example, in an unstable atmosphere, smoke column circulations can be strengthened which in turn may entrain additional oxygen from the surrounding environment to intensify the fire.

Various thermodynamic and severity indices have been developed to help fire managers assess severe weather potential and fire risks. Indices such as George's K, the Lifted Index, and the Total-Totals are used to predict thunderstorm development. In 1988, Haines introduced the lower atmospheric stability index (LASI) for wildland fires (Haines, 1988). LASI is based upon the stability and moisture content of the lower atmosphere. Low, middle and high level indices were developed to reflect regional elevations. An appropriate level is selected that is high enough above the surface to avoid significant diurnal variation. Research studies carried out in the United States have shown a relationship between the vertical structure of the atmosphere and fire activity (Werth and Ochoa, 1993).

Corresponding author address:

B. Kochtubajda, Meteorological Service of Canada, Room 200, 4999 98th Ave. Edmonton, AB. CANADA, T6B 2X3; e-mail: bob.kochtubajda@ec.gc.ca

The objectives of this study are to examine and compare the relationship of atmospheric severity indices and large-scale circulations with lightning activity and fire behaviour in the Northwest Territories. Two fire seasons were selected. The summer of 1995 was an extreme fire year, during which fires burned 2.8 Mha In 1998, another above average fire year, fires burned about 1.4 Mha**.**

2. STUDY AREA

The Mackenzie River Basin covers about 1.8 million km^2, and encompasses five fire management jurisdictions (see inset, Figure 1). The NWT extends poleward of the 60^{th} latitude and occupies about 47.1% of the basin area. The NWT is divided into five fire regions (Fig. 1).

The major topographic features include the Mackenzie Mountains west of the Mackenzie River and the Great Bear and Great Slave Lakes east of the River. The rocky Canadian Shield characterizes the eastern region of the NWT, while arctic tundra typifies the area in the north. The forested region of the NWT covers about 615,000 km^2. Black spruce, lodgepole, jack pines and trembling aspen are the common tree species in the NWT (Rowe 1972). Numerous small lakes and marsh areas dot the landscape.

The climate is influenced by several factors including: latitude, solar radiation, topography, and weather systems (Phillips, 1990). Although incoming solar energy which arrives at low angles limits the amount of surface warming, increased day-lengths in the summer offset this limitation. At Yellowknife, sunlight varies from about 20 h in June, while at Inuvik the sun does not set in the midsummer. Summer average monthly maximum temperatures are about 20°C, however, daily temperatures can reach well above 30°C.

Annual precipitation totals over the NWT range from 200 to 500 mm. Convective systems are a common feature during the summer months over most areas and they account for the majority of the annual precipitation (Stewart et al. 1998). However, there is considerable variation from year to year.

The convective storm season and resultant lightning activity is characterized as short but intense with a strong peak in cloud-to-ground lightning during June and July. The diurnal distribution of strikes indicates that most of the lightning is linked with daytime-heating initiated thunderstorms (Kochtubajda et al. 2001) .

Associated lightning activity can also generate major forest fires. Lightning typically starts approximately 80% of the forest fires in the NWT (Epp and Lanoville, 1996). Over the past 30 years, an annual average of about 310 fires have consumed approximately 650,000 ha in the NWT (Kasischke and Stocks, 2000). The number of fires and the area burned are highly variable from year to year (Fig. 2). The lowest and highest number of fires in any year occurred in 1997 and 1994, when 105, and 627 fires were started, respectively. The lowest area burned was 37,000 ha in 1974, while a record of more than 3 Mha of forest was consumed in 1994.

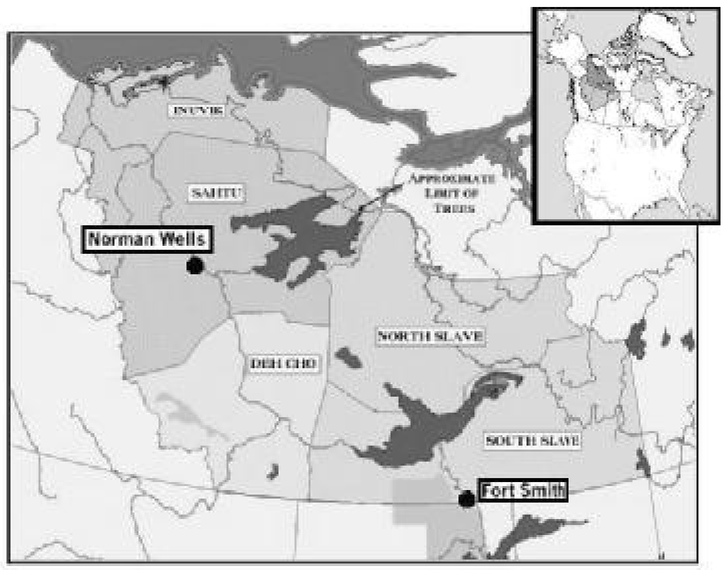

Figure 1: A map of the study area. The upper air stations used in the analysis are superimposed.

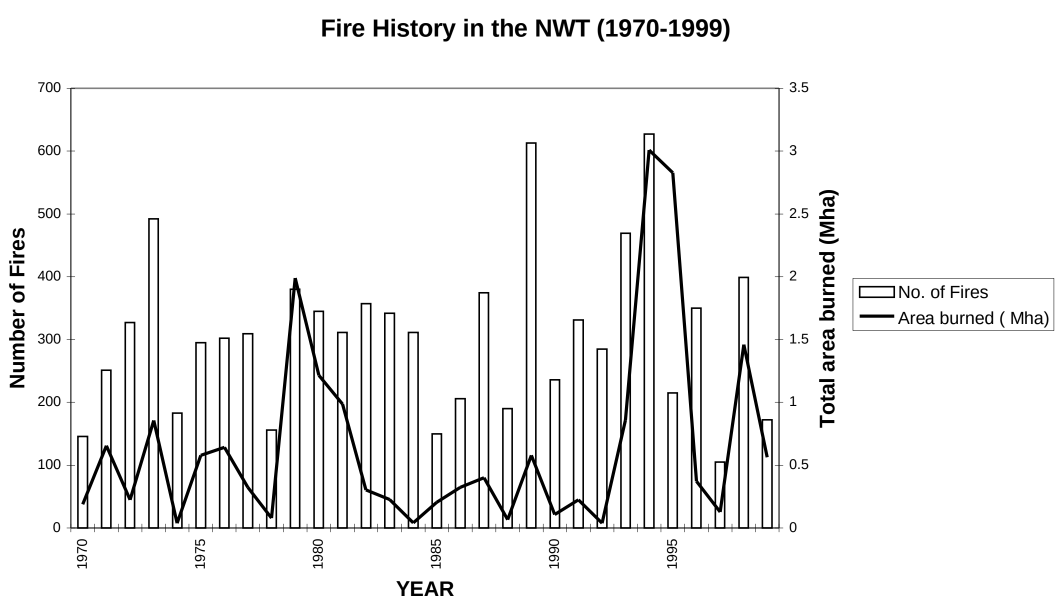

Figure 2: Annual variation of the number of fires and forest area burned in the Northwest Territories, from 1970 to 1999.

3. DATA AND METHODS

The study used a variety of data sources. These include the archived lightning strike data from the Northwest Territories government; fire data from the Canadian Forest Service's national Large Fire Database (Stocks et al. 2001), and the territorial fire database; sounding data from the Environment Canada upper air digital archive; and the historical gridded data from the National Centers for Environmental Prediction (NCEP).

Daily lightning strike statistics were determined from the lightning detection network archive operating in the Northwest Territories. The characteristics of the network are described in Kochtubajda et al. (2001).

Thermodynamic and severity indices were calculated from the 00 UTC radiosonde releases at the upper air stations near Fort Smith and Norman Wells (Fig. 1). The thermodynamic indices are defined in Table 1. The 00 UTC soundings were selected instead of the 12 UTC soundings because few "nocturnal" and early-morning lightning strikes are detected, and because the atmospheric conditions at this time are more representative of the conditions when forest fires are most active.

Data from the Norman Wells station were used to determine lapse rates and moisture values for all fires in the Inuvik, Sahtu, and Deh Cho regions, and the Fort Smith station was used for all fires in the North and South Slave regions. Haines' mid-level index was considered most applicable to the NWT (Haines, 1998).

The mid-level stability and moisture index was calculated by determining the temperature difference between the 850 and 700 mb levels and the atmospheric moisture content at the 850 mb level. The stability factor (A) is assigned a value between 1 and 3 based on the temperature lapse rate between the levels. If the temperature lapse rate between the 850 and 700 mb level is greater than or equal to 11°C, the stability factor is given a value of 3. If the lapse rate is less than 6°C, a value of 1 is given to the stability factor. The moisture factor (B) takes on a value between 1 and 3 based on the dew point depression at the 850 mb level. If the dew point depression is greater than or equal to 13°C, the moisture factor is assigned a value of 3. A value of 1 is given when the dew point depression is less than 6°C. The sum of the stability and moisture factors represents the Haines index of the potential for extreme fire behaviour for the day. The index values range from 2 to 6, where values of 2 to 4 generally represent a low potential for extreme fire behaviour, while higher values represent a greater likelihood of extreme fire behaviour.

Fires larger than 200 ha comprise the Large Fire Database. Although small in number, large fires account for approximately 97% of the total area burned (Stocks et al. 2001). Fires larger than 200 ha, 1000 ha, and 10,000 ha were used to determine whether a relationship between stability indices and fire size existed.

To investigate whether the various thermodynamic and severity indices were related to fire behavior we calculated the head fire intensity (HFI kW/m) for each large fire in the NWT during the 1995 and 1998 fire season using the Canadian Fire Behaviour Prediction (FBP) System (Forestry Canada 1992). We assumed a standard fuel type, black spruce, in this case. Meteorological variables required to calculate the HFI include temperature, relative humidity, wind speed and 24-h precipitation. These values were interpolated from surrounding meteorological stations in a procedure outlined in detail in Amiro et al. (2001). Using SAS version 8 we calculated the variance explained in the HFI using each index separately. We also calculated the variance explained in the daily lightning strike data using all the indices in SAS.

4. RESULTS and DISCUSSION

Stability, moisture and LASI index distributions for the large fires in both seasons are shown in Figure 3. The indices were also calculated for the entire 1995 and 1998 fires seasons (May 1 - Sep30) to provide a climatology on the relative frequencies of the indices. The analysis of the mid-level stability shows that Factor A is able to discriminate large fires. We found that less than 1% of the fires started when the mid-level temperature difference is less than 6°C and that about 60% of the fires began when the mid-level temperature difference is greater than 11°C.

The mid-level moisture, Factor B, on the other hand was not useful in discriminating large fires. About 20% of the fires were initiated when the dew point depression was greater than 13°C, and about 40% of the fires began when the dew point depression was less than 6°C. These observations differ from the Haines (1988) analysis which showed a majority (~60%) of fires beginning when the dew point depression was greater than 13°C, and about 9% of fires starting when the temperature-dew-point spread was less than 6°C. Our observations did not change significantly when fires larger than 1,000 ha, and 10,000 ha were considered. This suggests that either airmass characteristics in the NWT are different from those in the United States, or that the wind profiles in the 1995 and 1998 fire seasons were anomalous. Long-term averages at each upper air station may be required for proper comparisons. Another possible explanation is that the wind profiles from the upper air stations may not be entirely representative of the environment near some of the more distant fires.

Combining moisture and stability values also skewed the ability to discriminate large fires. Approximately 35% of the fires burned under a classification of very low potential for extreme fire behaviour. About the same percentage of days during the two fire seasons were classified as very low potential for large fires. Fifty-two percent of the fires burned on days with a moderate to high potential for extreme fire behaviour. Forty one percent of the fire season days were in these classiifications.

Relationships between the Haines Index and the fire, thermodynamic and lightning characteristics were examined. The median values of the fire area, the HFI, the Lifted Index, George's K, the Showalter Index, the Total-Totals Index and the daily cloud-to-ground lightning strikes for each index value and for different fire areas, are listed in Table 2. Several features are noted. Higher values of HFI , and more lightning activity are associated with higher values of LASI.

There were no statistically significant realationships (at the 95% level) between the HFI and any of the indices. A partial explanation for the poor performance is that we used only the day one HFI. Forest fires can burn days, weeks or until winter arrives. We can calculate the HFI for multiple days but we decided to examine the day the fire started first, to determine if there was any relationship. No apparent relationship was found. The upper air stations in Fort Smith and Norman Wells were a long way from some of the fires and it is possible that the vertical structure of the atmosphere and the associated indices were quite different at the fire site.

Two indices, the lifted index and Showalter index were significantly related to daily lightning activity. A scattergram of the lifted index and daily lightning is shown in Figure 4. The lifted index explained 31% or the variance in the lightning data while the showalter explained almost 14%. No other index explained over 10% of the variance. These results are promising and additional analyses are needed.

To assess the large-scale atmospheric circulation in association with fire incidents, we utilized the NCEP reanalysis global gridded data, (Kalnay et al. 1996), to produce composite, or averaged, geopotential fields at 500 hPa. Anomalies, with respect to a 35-year monthly climatology were also produced. The composites were produced for LASI values of 3 and 5 for those cases with areal coverage greater than 1000 ha. We found 13 dates that were separated by at least 3 days for LASI values of 5, and 12 dates, similarly defined for LASI values of 3. The number of dates found is less than the numbers shown in Table1, because multiple fires occurred on particular days.

Figure 5, showing the composites for LASI values of 5, shows a coherent trough that travels eastward from the Pacific into coastal areas of Alaska. The downstream ridge line passes to the east of the NWT fire region by the onset of the fires at T0. This typically signifies the beginning of large-ascent that triggers a potentially unstable environment into the production of thunderstorms. There was no such coherent signal observed for the LASI-valued composite of 3. The fact that the former composite has substantially more lightning suggests that the preferentially-strong lightning count is a consequence of a synoptic-scale trigger in the form of an upper-level trough that travels eastward from the Pacific basin.

5. SUMMARY

A study was undertaken to examine atmospheric instability and large-scale circulation influences on fire behaviour in the NWT. Preliminary results indicate that no one index was shown to be a strong indicator of large fires over the NWT and over these two fire seasons. The mid-level Haines index was not sensitive enough in classifying the potential for extreme fire behaviour. The moisture component seems to be the limiting factor. This suggests that airmass characteristics in the NWT may have been different during these two fire seasons. Long-term averages at each upper air station may be required for proper comparisons. Several other factors may also account for the poor performance including, different fuel complexes , a different climate, and longer days.

Correlation analyses suggest a potential predictive capability between several thermodynamic indices and lightning activity. Furthermore, for fires greater than 1000ha, a very coherent large-scale circulation anomaly structure is associated on days with LASI values of 5 that is absent on days with LASI values of 3. Further analyses are warranted .

Analyses are also planned to examine the influences of low-level wind speed and direction, antecedent precipitation conditions, and the 12-hr change in 500 mb height on the behaviour of these large fires.

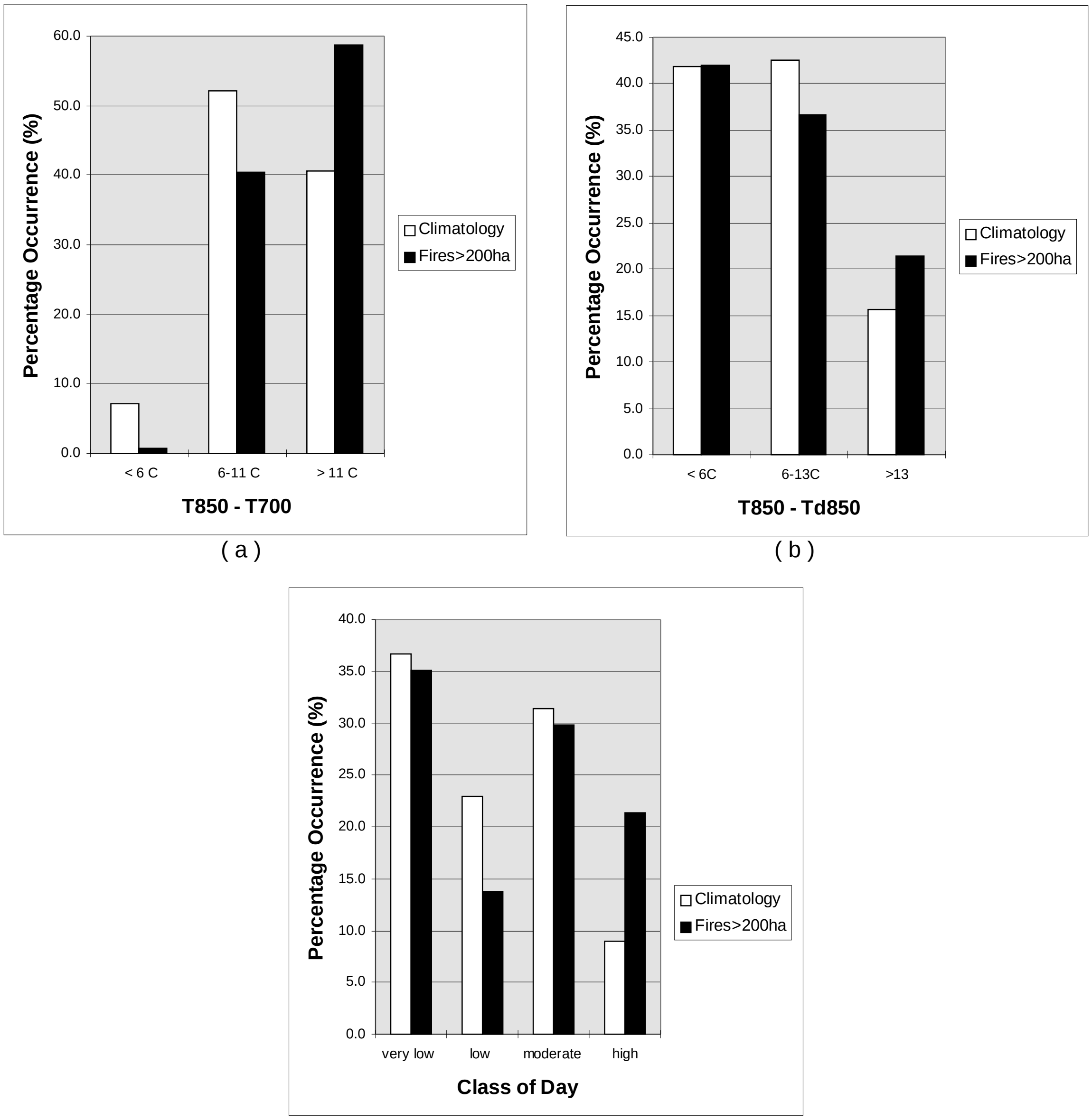

Figure 3: The mid-level stability (a), moisture(b), and LASI index characteristics(c) for fires > 200 ha during the 1995 and 1998 fire seasons.

6. ACKNOWLEDGEMENTS

Funding support for this study was provided by Prairie and Northern Region of Environment Canada, and by the Natural Sciences and Engineering Research Council of Canada.

We are grateful to Bob Crawford for his assistance in preparing Figure 1, to Monique Lapalme, Pat Kyle and Brian Wiens for their assistance with the upper air data, to Kim Logan for generating the HFI dataset, and to Rick Lanoville and Jennifer Patriquin of the Government of the Northwest Territories, Forest Management Division in Fort Smith who provided the lightning data.

7. REFERENCES

Amiro, B.D., Todd, J.B., Wotton, B.M., Logan, K.A., Flannigan, M.D., Stocks, B.J., Mason, J.A., Martell, D.L., and Hirsch, K.G., 2001: Direct carbon emissions from Canadian forest fires, 1959 to 1999, *Can. J. For. Res*. **31**, 512-552.

Epp, H., and R. Lanoville, 1996: Satellite data and geographic information systems for fire and resource management in the Canadian Arctic. *Geocarto International*, **11**, 97-103.

Forestry Canada 1992. Development and structure of the Canadian forest fire behavior prediction system. Info. Rep. ST-X-3. Canadian Forest Service, Ottawa.

Galway, J.G., 1956: The lifted index as a predictor of latent instability. *Bull. Amer. Meteor. Soc*., **37**, 528-529

George, J.J., 1960: *Weather forecasting for aeronautics*. Academic Press, New York. 673pp

Haines, D.A., 1988: A lower atmosphere severity index for wildland fires. *National Weather Digest,* **13,** 23-27.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K.C. Mo, C. Ropelewski, J. Wang, A. Leetmaa, R. Reynolds, R. Jenne, and D. Joseph. 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Am. Meteorol. Soc*., **77**, 437-471.

Kasischke, E.S., and B.J. Stocks (editors) 2000: *Fire, Climate Change and Carbon Cycling in the Boreal Forest*. Ecological studies 138. Springer-Verlag, New York, 461 pp.

Kochtubajda, B., R. Stewart, J. Gyakum, and M. Flannigan, 2001: Summer convection and lightning over the Mackenzie River basin and their impacts during 1994 and 1995. *Atmos.-Ocean* (*accepted for publication*)

Miller, R.C., 1972: *Notes on analysis and severe-storm forecasting procedures of the Air Force Global Weather Central.* Tech. Rep. 200, Air Weather Service (MAC), USAF, Offut, Neb., May, 1972, 102 pp.

Phillips, D., 1990: *The Climates of Canada*. Canadian Government Publishing Centre, Supply and Services Canada. Ottawa, ON., 176pp

Rowe, J.S. 1972. *Forest Regions of Canada*. Dept. of Fisheries and the Environment. Canadian Forestry Service, Publication No. 1300. 172 pp.

Showalter, A.K., 1953: A stability index for thunderstorm forecasting. *Bull. Amer. Meteor. Soc*., **34**, 250-252.

Stewart, R.E., H.G. Leighton, P. Marsh, G.W.K. Moore, H. Ritchie, W.R. Rouse, E.D. Soulis, G.S. Strong, R.W. Crawford, and B. Kochtubajda, 1998: The Mackenzie GEWEX Study: The water and energy cycles of a major North American river basin. *Bull. Amer. Meteor. Soc.,* **79,** 2665-2683.

Stocks, B.J., J.A. Mason, J.B. Todd, E.M. Bosch, B.M. Wotton, B.D. Amiro, M.D. Flannigan, K.G. Hirsch, K.A. Logan, D.L. Martell, and W.R. Skinner, 2001: Large forest fires in Canada, 1959-1997. *J. Geophy. Res. (accepted for publication)*

Werth, P., and R. Ochoa, 1993: The evaluation of Idaho wildfire growth using the Haines Index. *Wea. And Forecasing,* **8,** 223-234.

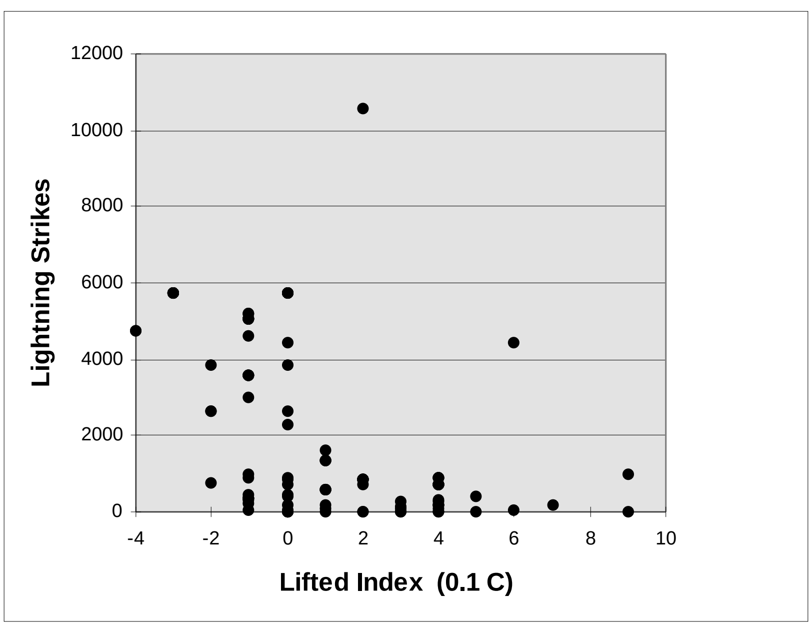

Figure 4: Scattergram of the Lifted Index and Daily Lightning Strikes

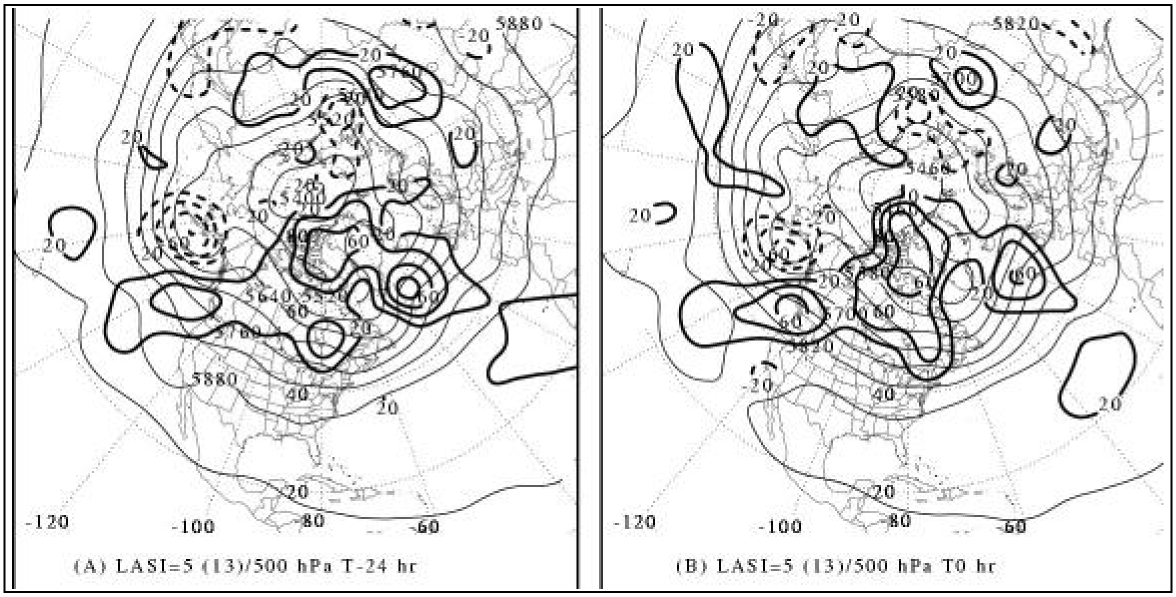

Figure 5: A 13-case composite of 500-hPa height (light solid, interval of 60 m), and anomaly (interval of 20 m; heavy solid for positive, heavy dashed for negative) for (a) 24 h prior to the fire onset and (b) the onset of the fires.

Table 1: Stability indices and their definitions

INDEX	***Definition***	***Reference***
Showalter	SI = T500 - LT800	Showalter, 1953
George's K	K = (T850-T500) + Td850 - (T700-Td700)	George, 1960
Lifted Index	LI = T500 - LTsfc	Galway, 1956
Total-Totals	TT= (T850-T500) + (Td850 - T500)	Miller, 1972
SWEAT Index	SWEAT = 12*Td850 + 20(TT-49) + Ws500 + 125 (sin(Wd500-Wd850) +0.2)	Miller, 1972

Table 2: Fire, thermodynamic and lightning characteristics and the LASI Haines Index.

LASI	Fires	Area	HFI	LI	KI	SHOW	Total-Totals	Lightning
Area >200ha								
3	44	2750	2274	0.4	29	2	45	768
4	18	5250	5378	0.1	26	2.5	48	738
5	39	5000	4408	-0.1	25	0	50	4763
6	28	3650	11225	0.1	23	2	47	3262
Area >1000ha								
3	34	4075	2146	0.4	29	2	46	768
4	14	17500	5378	0	30	1	48	1220
5	31	10000	6619	-0.1	25	1	50	3868
6	23	5500	9721	0.1	23	2	47	3262
Area >10000ha								
3	11	18750	1649	0.4	30	3	44	909
4	8	45000	3472	0.1	24	2.5	49	667
5	16	43000	8371	-0.3	27	0	51.5	4234
6	8	30170	11849	0	24	1	48	4763