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A 500 hPa synoptic wildland fire climatology for large Canadian forest fires, 1959–1996

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With 5 Figures

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Summary

In Canada, the average annual area of burned forest has increased from around 1 million ha in the 1970's to over 2.5 million ha in the 1990's. A previous study has identified the link between anomalous mid-tropospheric circulation at 500 hPa over northern North America and wildland fire severity activity in various large regions of Canada over the entire May to August fire season. In this study, a northern North American study region of the hemispheric gridded 5° latitude by 10° longitude 500 hPa dataset is identified and analysed from 1959 to 1996 for a sequence of six monthly periods through the fire season, beginning in April and ending in September. Synoptic types, or modes of upper air behavior, are determined objectively by the eigenvector method employing K-means cluster analysis. Monthly burned areas from the Canadian Large Fire Database (LFDB) for the same period, 1959 to 1996, are analysed in conjunction with the classified monthly 500 hPa synoptic types. Relationships between common monthly patterns of anomalous upper flow and spatial patterns of large fire occurrence are examined at the ecozone level. Average occurrence of a monthly synoptic type associated with very large area burned is approximately 18% of the years from 1959 to 1996. The largest areas burned during the main fire (May to August) season occur in the western Boreal and Taiga ecozones – the Taiga Plains, Taiga Shield, Boreal West Shield and Boreal Plains. Monthly burned areas are also analysed temporally in conjunction with a calculated monthly zonal index (Zi_m) for two separate areas defined to cover western and eastern Canada. In both western and eastern Canada, high area burned is associated with synoptic types with mid-tropospheric ridging in the proximity of the affected region and low Zi_m with weak westerlies and strong meridional flow over western Canada.

1. Introduction

Forests cover approximately 45% of the Canadian land area. Wildland fires can burn millions of hectares of forests annually. In addition, fire disturbance in the northern forests is recognized as affecting global sources and sinks of carbon dioxide (Kurz and Apps, 1999). The number of wildland fires appears to have been steadily increasing since 1960 with the reported area burned in some regions of Canada tripling from 1980 to the present (Stocks et al., 2001). In addition, the five worst Canadian fire years since 1918 have taken place in the past 15 years.

The long term average of area burned across a landscape is determined by a complex set of variables including the size of the sample area, the period under consideration, the extent of the forest, the topography, fragmentation of the landscape (rivers, lakes, roads, agricultural land), fuel characteristics, season, latitude, fire suppression policies and priorities, fire control, organizational size and efficiency, fire site accessibility, ignitions (people and lightning), simultaneous fires and the weather. Stocks et al. (1996) examined the spatial distribution of large fires in Canada during the 1980s and found that the greatest area burned occurred in the boreal region of west-central Canada. This was attributed to a combination of factors including fire-prone ecosystems, extreme fire weather, lightning activity, and varying levels of protection in this region. In the wake of the severe 1995 fire season, there has been renewed effort to better understand the processes that influence wildland fire in Canada.

The annual area burned by forest fires in Canada can vary by more than an order of magnitude between successive years (i.e. from 0.5 million to 7.5 million hectares), and is expected to increase with climate change (Stocks et al., 1998). Canadian forest fires also produce highly variable fluxes of carbon to the atmosphere annually, averaging 27 Tg C/year over the 1959–1999 period (Amiro et al., 2001). The Canadian boreal forest has adapted to, and is constantly being renewed by, periodic fire, which is recognized as a major driver of the global carbon balance, including the sink/source strength of these forests over the short term. As a result of increased fire and insect disturbances over the past three decades, Canadian forests have become a recent carbon source (Kurz and Apps, 1999).

Nimchuk (1983) related two episodes of catastrophic burning during the Alberta 1981 fire season to the breakdown of the upper ridge over Alberta. These episodes, which lasted 8 days, accounted for about one million ha burned. The breakdown of these upper ridges are often accompanied by increased lightning activity as upper disturbances (short-waves) move along the west side of the ridge. Additionally, as the ridge breaks down, strong and gusty surface winds are common. Brotak and Reifsnyder (1977) found that the vast majority of large fires (over 200 ha) in the eastern United States were associated with the eastern section of an intense short-wave trough at 500 hPa. A recent study by Skinner et al. (1999) has identified a significant statistical association between May to August fire season total area burned on a large regional multi-provincial scale and anomalous flow in the mid-troposphere, indicating the control of large-scale climatological features on the location and severity of large area burned in Canada. Also, climate modeling experiments by Lupo et al. (1997) suggest increases in blocking ridges in the future.

Recent assessments of projected climate change impacts on forest fire activity (e.g. Stocks et al., 1998) clearly indicate that increases in regional seasonal fire weather severity will result in large increases in the areal extent of extreme fire danger at northern latitudes. The accurate prediction of future Canadian fire regimes therefore requires the identification of relationships between synoptic-scale climate variability and forest fire impacts (for example, 500 hPa ridging frequency and strength and area burned at high spatial and temporal resolution) that will be reconcilable with future Regional Climate Model (RCM) (Caya et al., 1995) results. The purpose of this study is to establish baseline associations between classified patterns of large-scale mid-tropospheric circulation at 500 hPa and wildland fire severity at high spatial (ecozone) and temporal (monthly) resolution using the newly developed Canadian Large Fire Database (LFDB) (Stocks et al., 2001). This information would aid in predicting wildland fire location and severity in Canada. Also, an improved knowledge of current climate-fire relationships would be useful for assessing potential changes in wildland fire regimes due to future climate change for future operational and policy-planning efforts in the forest industry.

In addition, current and future negotiations subsequent to the Kyoto Protocol require a thorough quantification of the carbon balance dynamics of Canadian forests, including the limited likelihood of these forests providing an offset to fossil fuel emissions in the future, particularly as disturbance regime impacts increase with climate change. In addition, there is a need to identify in aggregate terms, the spatial and temporal variability of the levels of fire protection that have been brought to bear on our study regions over time.

2. Study region and data

2.1 Northern hemisphere 500 hPa heights

The upper air data base consists of daily (1200 UTC) 500 hPa geopotential height values for the Northern Hemisphere from 15° N to the pole on a 455-point grid from 1946 to 1998. The grid has a spatial resolution of 5° latitude by 10° longitude from 15° to 65° N, and 5° latitude by 20° longitude from 70° N to the pole. The data from 1946 to 1981 were obtained from the National Centre for Atmospheric Research (Jenne, 1975) and the balance, 1982 to present, from the Canadian Meteorological Centre in Montreal. A detailed description of the 500 hPa height data set is given in Knox et al. (1988). The daily 500 hPa heights are averaged by calendar month intervals for each grid point. Monthly 500 hPa height anomalies, expressed in decameters (dams), are calculated at each grid point based on the full period (1946–1998) average.

A northern North American study region of the hemispheric gridded dataset is identified for further analysis (Fig. 1). The study region extends from 45° N to 75° N and 50° W to 150° W. It was decided to focus on this study region because a previous study (Skinner et al., 1999), which examined the entire hemispheric dataset in relation to multi-provincial area burned totals, identified extremely high area burned fire seasons were clearly associated (statistical significance) with highly anomalous ridging immediately over and to the west of the affected large region. For this study, the upper air data are examined for the period 1959 to 1996 to correspond with complete national coverage in the LFDB.

The average 500 hPa heights from 1959 to 1996 for July (example of high summer) are shown in Fig. 2. The main features which affect northern North America are indicated. They include from west to east: a weak southward-extending trough located adjacent to the west coast of North America; a parallel strong northward-extending ridge over western and north-western Canada ranging from the west coast of North America to approximately 110° W and extending from mid-latitudes to Alaska; and a strong southward-extending trough over north-eastern North America. This eastern trough has been termed the Canadian Polar Trough (CPT) during winter (Shabbar et al., 1997). In summer, the spatial domain of CPT, is much weaker. However, it still dominates north-eastern North America extending from and including the closed circulation over northern Baffin Island, to the mid-latitudes where it broadens to occupy a sector from approximately 100° W to 50° W. The western and north-western Canada ridge is slightly more pronounced and has further southward extension in the spring months (April–May) than in summer (June–August). Also, the

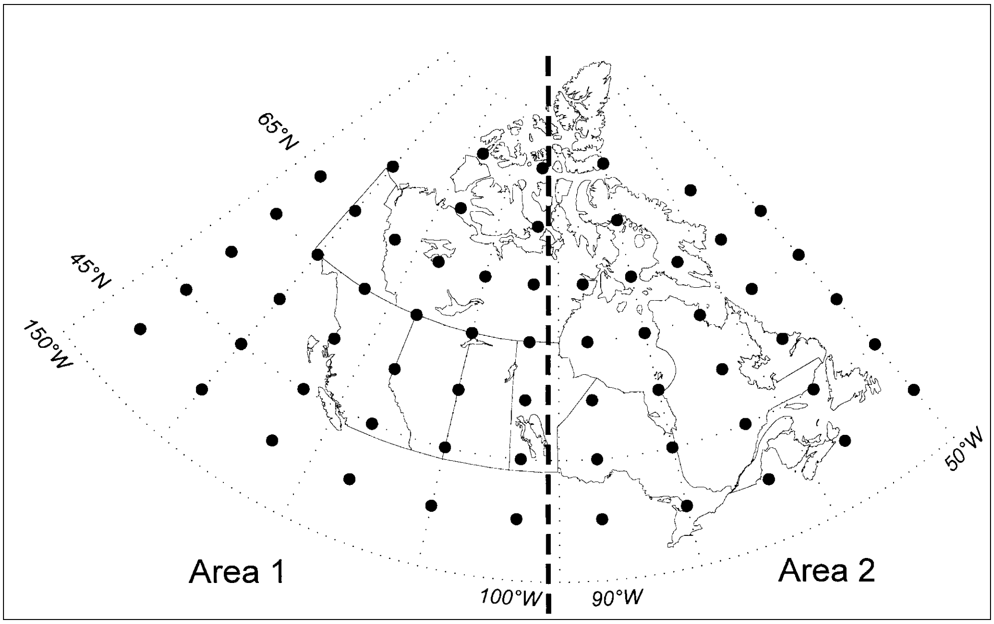

Fig. 1. Study region and 500 hPa height grid for synoptic wildland fire climatology analysis partitioned into Area 1 (western Canada) and Area 2 (eastern Canada) for calculation of monthly zonal index (Zi_m)

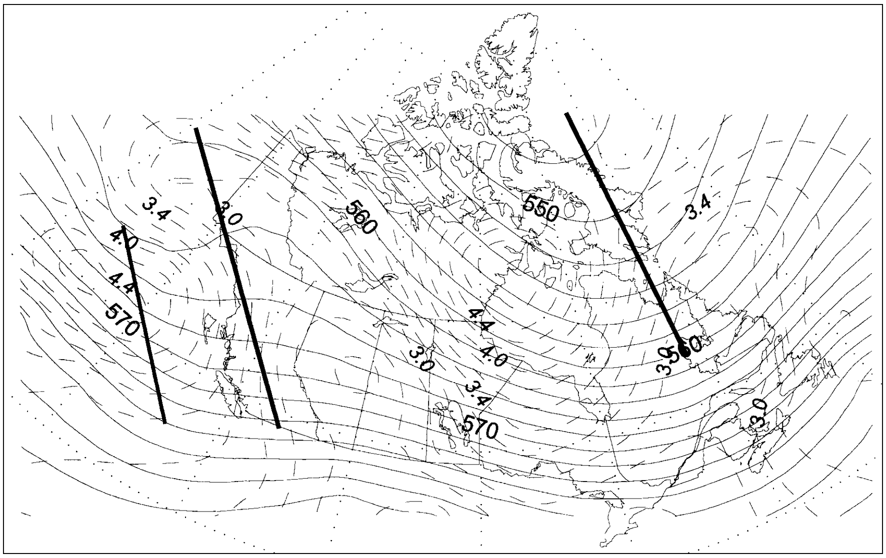

Fig. 2. Average 500 hPa circulation (solid line contour interval 2 dams) and average 500 hPa standard deviation (dashed line contour interval 0.2 dams) for the period 1959 to 1996 for July for the northern North American study region. Vertical lines represent the main features affecting northern North American climate. From west to east these are: west coast trough; continental ridge; Canadian Polar Trough (CPT)

atmosphere is generally thicker (higher 500 hPa heights) over all of Canada during summer than during spring.

During normal late spring and summer conditions, moisture-bearing systems from the Pacific Ocean are generally deflected away from the forested north-western, western and west-central regions of Canada thus producing drier climate conditions. East-central and eastern Canada is normally subjected to an abundance of moisture-bearing systems, generally originating from the south and southwest. Surface low-pressure system development is greatest in the baroclinic zone where the jet stream is strongest, in the southern areas of CPT. Eastern Canada therefore normally experiences more humid climate conditions than its NW, western and west-central counterparts.

The standard deviation of 500 hPa heights, as calculated over the period 1959 to 1996 at each grid point for July, are also shown in Fig. 2. The standard deviation map reveals major centres of higher variability affecting northern North America during the peak of the fire season, including central Canada, and the north Pacific Ocean. During late spring (not shown) a large centre of higher variability is evident over north-central Ontario (> 5.0 dams), while during summer this centre has migrated northward to the northern Hudson Bay region (> 4.8 dams). There is also a weaker centre of higher variability over Alberta (> 3.6 dams), an important feature for it is located in the vicinity of the western North American ridge and in the vicinity of the highest percent annual area burned (PAAB) regions of Canada (Stocks et al., 2001). These centres are somewhat transitory for individual months and are generally stronger earlier (late spring) and later (early fall) in the fire season. While the trough-ridge-trough represents the normal summer flow configuration across northern North America, there is considerable variability in both the monthly and seasonally averaged patterns.

2.2 Canadian Large Fire Database (LFDB)

Area burned by wildland fire is defined as "all land on which wildfires occur, including forest, cutover forest, grasslands, scrub, etc." (Flannigan and Harrington, 1988). For this study, the area analysed consists of all Canadian provinces and territories. The Canadian Large Fire Database (LFDB) is a record of reported fires in Canada that exceed 200 ha in size (Stocks et al., 2001). Because the record lengths vary by reporting provincial agency, this study is restricted to 1959 to 1996, the common period of complete national data coverage in the database from all provincial agencies. Pertinent information in the LFDB includes precise spatial coordinates, start date of fire, total area burned, the cause of the fire if known, and the ecozone in which the fire started.

The use of the Canadian LFDB represents a marked improvement over previous studies which were restricted to provincial totals of area burned

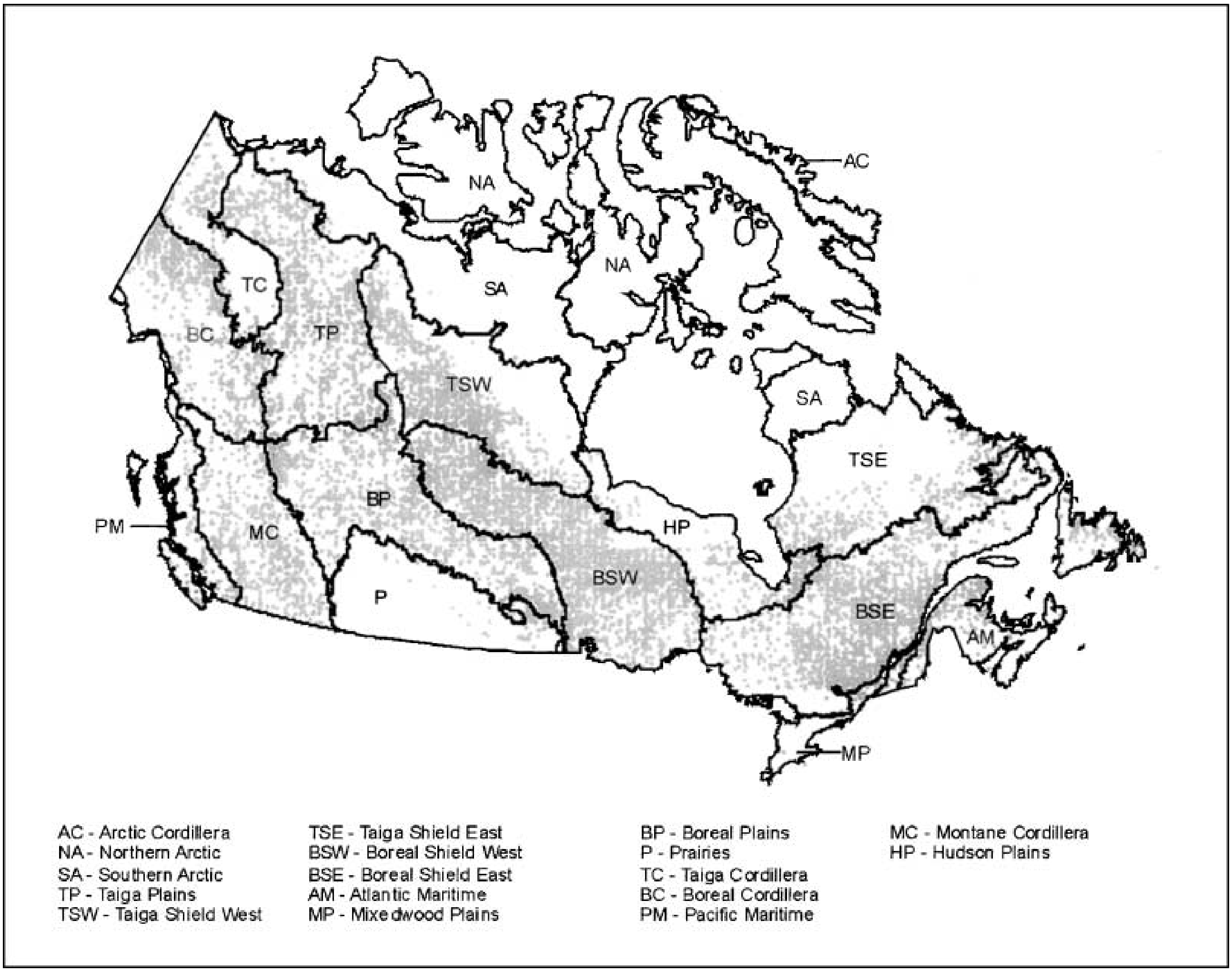

Fig. 3. Terrestrial ecozones of Canada and geographical distribution of 1959–1997 LFDB fires across Canada

(Harrington, 1982; Harrington et al., 1983; Flannigan and Harrington, 1988; Skinner et al., 1999). For this study, only lightning caused fires are analysed. The inclusion of human-caused fires in the analysis would spatially bias the results to the southern, more populated margins of the boreal forest. Large fire/500 hPa relationships are examined at the ecozone level (Fig. 3). The ecozone configuration (Ecological Stratification Working Group, 1995) is used in this study because this classification is based largely on vegetational distribution. For this study, the Boreal Shield and Taiga Shield ecozones are subdivided into the Boreal Shield West and the Boreal Shield East, and Taiga Shield West and Taiga Shield East. Figure 3 also shows the geographical distribution of 1959–1997 LFDB fires across Canada.

The frequency of large fires within an ecozone is often represented by determining the percent annual area burned (PAAB), which takes ecozone size into account (Stocks et al., 2001). PAAB figures are highest in the Taiga Shield West and Boreal Shield West ecozones, and almost as high for the Taiga Plains ecozone. In these combined areas an average of 0.75% of the land area burns annually. Fire affects significant portions of the Taiga Shield East, Boreal Shield East, Boreal Plains, and Boreal Cordillera ecozones as well, but is not a major factor, in terms of area burned, in the remaining Canadian ecozones.

3. Methods

Grids of 500 hPa geopotential height anomalies for the northern North American study area for each month in the fire season (April–September) from 1959 to 1996 (Fig. 1) were classified using the eigenvector-based map-classification method (Yarnal, 1993). A previous study has employed the eigenvector method to classify monthly middle atmosphere circulation patterns in relationship to surface temperature patterns and severe wildland fires by large region in the continental U.S.A. (Heilman, 1995). Also, in a previous study, synoptic circulation types (gridded pressure fields) were classified at a smaller regional scale (southwestern British Columbia) to examine the relationships with ground level ozone concentrations in the lower Fraser Valley (McKendry, 1994; Pryor et al., 1995).

A correlation matrix for each monthly grid is determined because it is not affected by variance gradients as is the covariance matrix. The correlation matrix is subsequently entered into a principal components analysis (PCA). The principal components for each month are rotated orthogonally because this provides a more meaningful measure of each components importance. The monthly component-scores matrices are then clustered by the K-means clustering method in order to identify the most common combinations of principal-component scores. Monthly scree plots are analysed for significant breaks in slope to determine the number of clusters to retain. The most common number of clusters retained is six. Average actual and anomalous 500 hPa height maps are then calculated from the grids for the years defined in each cluster, or synoptic type.

Total area burned from the Canadian LFDB is analysed by ecozone (Fig. 3) in conjunction with the objectively classified mid-tropospheric synoptic types to determine the relationships between large fire occurrence, in terms of total area burned, and common patterns of mid-tropospheric flow. In order to identify the synoptic types associated with the largest areas burned, the areas burned are totaled for the years identified in each synoptic type and then categorized by percent frequency by ecozone. All synoptic types which comprise at least 70% of the national total area burned for a given month are selected. The ecozones with the greatest areas burned (totaling at least 80%) are identified for each synoptic type.

Mean monthly zonal index (Zi_m) values are calculated from the 500 hPa geopotential heights for two areas over the study region (Area 1 and Area 2 in Fig. 1). This index is commonly used to characterize the type of circulation over a geographic region (Makrogiannis et al., 1991). The Zi_m for Area 1, bounded by longitudes 150° W and 95° W, describes flow for western Canada, while the Zi_m for Area 2, bounded by longitudes 95° W and 50° W, describes flow for eastern Canada. For this study, the index is defined as the mean 500 hPa pressure height difference between 45° N and 65° N

$$Zi_m = (500\,\text{hPa height}_{45^\circ\text{N}}) - (500\,\text{hPa height}_{65^\circ\text{N}})$$

A "high index" is denoted when the difference is high and defines a state with strong westerlies and thus weak meridional flow within the defined latitudes. A "low index" is denoted when the difference is low and defines a state with weak westerlies and strong meridional flow in the same latitudes.

4. Results

4.1 500 hPa height patterns and large area burned

Table 1 shows the percent frequencies of total area burned by ecozone for each monthly synoptic type. There are several important features of this analysis. Firstly, is the shoulder months of the fire season in Canada have a small number of synoptic types that are associated with large area burned (one in April, two in August, two in September) while during the main fire season (May, June and July) when the largest burned areas occur, 50% of synoptic types are associated with large fire activity. Secondly, it is important to note that large area burned is infrequent in April and September. Nationally, total area burned in April and September comprise less than 2% of the entire fire season, while May (approximately 8%) and August (approximately 13%) are important but relatively small compared to the totals during the peak months of June (approximately 41%) and July (approximately 37%). In addition, as outlined by Stocks et al., 2001, the largest areas burned during the main fire season are clustered spatially in the relatively dry climates of the western Boreal and Taiga

Table 1. Percent frequency of monthly large area burned by synoptic type, nationally and by ecozone. Boldfaced denotes the most important synoptic type in a given month and boldfaced underlined denotes the percent area burned in the most important ecozone for that synoptic type

Ecozone	April	May	June	July	August	September
National **T** = synoptic type	***T6*** 98%	***T4***, T6, T2 67%, 13%, 10% (90%)	***T5***, T2, T6 32%, 28%, 18% (78%)	***T6***, T1, C4 51%, 15%, 13% (79%)	***T5***, T2 46%, 30% (76%)	***T3***, ***T6*** 36%, 36% (72%)
Southern Arctic						
Taiga Plains			***34%***, 9%, 32%	***27%***, 41%, 18%	18%, 16%	13%
Taiga Shield West			50%	18%, 14%, 24%	24%	
Taiga Shield East			22%	10%	12%	
Boreal Shield West	***76%***	39%, 56%, 56%	20%, 28%, 15%	***28%***, 30%, 11%	22%, 34%	***91%***
Boreal Shield East		42%	9%	23%		
Atlantic Maritime						
Mixedwood Plains						
Boreal Plains	24%	***51%***, 36%,	15%		***41%***	***79%***
Prairies					13%	
Taiga Shield						
Boreal Cordillera			27%			
Pacific Maritime						
Montane Cordillera						
Hudson Plains						

ecozones; the Taiga Plains, Taiga Shield West, Boreal Shield West, and Boreal Plains. Lastly, the monthly large-scale synoptic patterns associated with the largest areas burned in April (Type 6), May (Type 4), June (Type 5), and July (Type 6) all have very similar structure. The monthly patterns associated with large areas burned in late summer and fall (August and September) are different from those of importance in spring and summer.

Figure 4a and 4b show the synoptic types which correspond to the highest percent frequency of national area burned for June and August, respectively. The large fires which occurred during each of these monthly synoptic types are also identified by ecozone. All ecozones contributing to area burned totals greater than 90% for the synoptic type are included. For example, in June (Fig. 4a), 32% of the total national area burned occurred in synoptic type 5 in which 85% of that fire burned in the Boreal Shield West and Boreal Shield East, Taiga Shield East, and Taiga Plains ecozones (see also Table 1). In August (Fig. 4b), 46% of the total national area burned occurred in synoptic type 5 in which 94% of that fire burned in the Boreal Shield West, the Taiga Plains, the Prairies, and the Boreal Plains ecozones (see also Table 1).

Figure 4a shows the actual and anomalous 500 hPa height flow for June synoptic type 5. This type accounted for 32% of the total area burned nationally. For this type, 85% of the large area burned occurred in the Boreal Shield West and Boreal Plains ecozones, as well as northward extension to the Taiga Plains and eastward extension to the Boreal Shield East ecozones. The greatest area burned during the influence of this

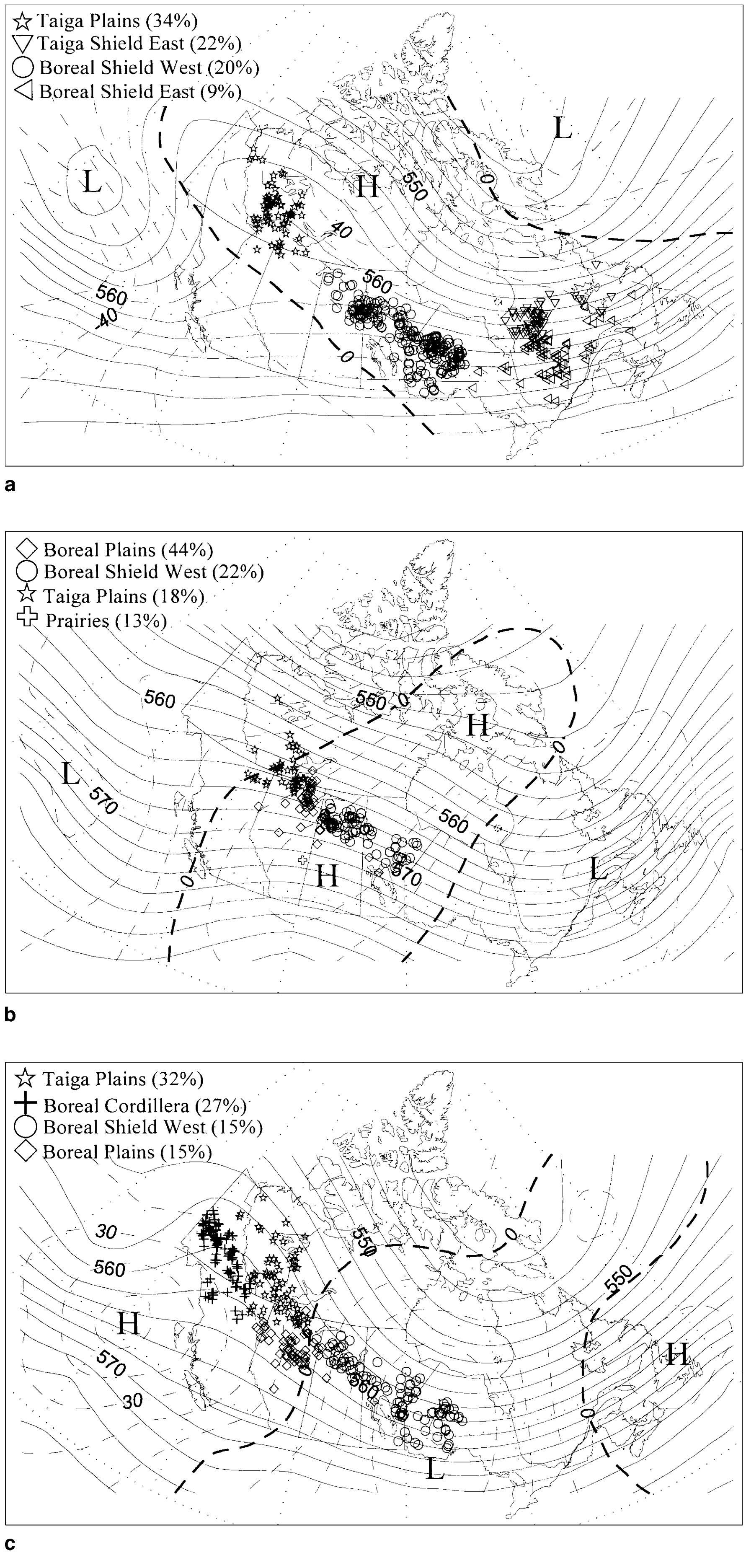

Fig. 4. Monthly 500 hPa synoptic types associated with large area burned, and locations of large fires by ecozone for (**a**) June Type 5 (32% of total area burned nationally), (**b**) August Type 5, (76% of total area burned nationally), and (**c**) June Type 6, (18% of total area burned nationally). Solid lines are average actual heights (contour interval 2 dams) and dashed lines are average anomalous heights (contour interval 10 dams, zero interval is bold) for the years in each synoptic type

synoptic type occurred in the Taiga Plains ecozone (34%). The actual and anomalous 500 hPa height flow for April synoptic type 6, May synoptic type 4, and July synoptic type 6 are all very similar with an expanded and deeper than normal trough off the west coast and a highly anomalous western ridge and weaker than normal CPT. This is the most common pattern associated with large area burned during spring and early summer in Canada.

Figure 4b shows the actual and anomalous 500 hPa height flow for August synoptic type 5. This type accounted for 46% of the total area burned nationally in that month. For this type, 94% of the large area burned occurred in the Boreal Shield West, Boreal Plains, Taiga Plains and the Prairie ecozones (one large fire (438,000 ha) occurred in 1981 at 53° N, 111° W). The greatest area burned during the influence of this synoptic type occurred in the Boreal Plains ecozone (41%). Anomalous 500 hPa flow contributing to large area burned is confined to higher than normal heights in south-western and north-eastern Canada and a strong west coast trough as well as in the southerly limits of CPT. Anomalous 500 hPa flow for September synoptic type 3 not shown is also unique when compared to the earlier months. 500 hPa heights over most of Canada are lower than normal leading to zonal flow and strong westerlies. Area burned in this month is low with respect to the seasonal totals and is confined to individual severe years.

In most large area burned cases, the trough located off the west coast is much deeper than normal and the continental ridge is much higher than normal, often with eastward extension resulting in a weaker CPT. Flow in the mid-troposphere over western Canada is highly meridional (low index with weak westerlies) with moisture-bearing systems from the Pacific being deflected away from western and west-central Canada. Also, storm development in the baroclinic zone on the southern limits of CPT would be retarded with reduced moisture by the high summer months.

Synoptic types associated with large area burned are also important on a regional spatial scale. May synoptic type 2 (not shown) accounted for just 10% of the total area burned nationally, however 98% of the large area burned in this synoptic type occurred in the eastern areas of the Boreal Shield West (56%) and the Boreal Shield East (42%) ecozones. Anomalous 500 hPa flow is unique with 500 hPa heights over western Canada lower than normal (deep west coast trough and weak ridge) leading to zonal flow and strong westerlies but much higher than normal heights over central and eastern Canada resulting in a very weak CPT, possibly even weak ridging.

June synoptic type 6, shown in Fig. 4c, accounted for 18% of the total area burned nationally of which 89% of the large area burned occurred in the western and north-western ecozones, the Taiga Plains, Boreal Cordillera, Boreal Shield West and Boreal Plains. The greatest areas burned during the influence of this synoptic type occurred in the Taiga Plains (32%) and Boreal Cordillera ecozones (27%). Anomalous 500 hPa flow is also unique with 500 hPa heights over extreme western Canada much higher than normal (upper level blocking with no west coast trough and strong ridge) leading to meridional flow and weak westerlies over western, north-western, and central Canada.

July synoptic type 1 (not shown) accounted for 15% of the total area burned nationally of which 85% of the large area burned occurred in the western and north-western ecozones, the Taiga Plains, Boreal Shield West and Boreal Plains. Anomalous flow is similar to the previous example ecozone (upper level blocking with no west coast trough and strong ridge) but with southwest migration of the higher than normal heights having little blocking influence on the extreme northwest (Boreal Cordillera).

4.2 Zonal index (Zi_m)

Table 2a and 2b show calculated $\mathrm{Zi_m}$ for each synoptic type by month for Area 1 and Area 2 (Fig. 1), respectively. A "high index" is denoted when the index is high and defines a state with strong westerlies and thus weak meridional flow within the defined latitudes. A "low index" is denoted when the index is low and defines a state with weak westerlies and strong meridional flow in the same latitudes. For Area 1, the lowest index values occur in the largest area burned synoptic types for the months April (type 6), May (types 4 and 6), June (type 5), and July (type 6). This relationship does not exist for

Table 2. Calculated monthly zonal index (Zi_m) for each synoptic type by month for (**a**) Area 1 and (**b**) Area 2. Boldfaced and underlined values denote the highest area burned synoptic type as described in Table 1. Boldfaced values denote synoptic types of secondary importance as described in Table 1

Synoptic Type	April	May	June	July	August	September
(a)						
1	27.74	24.43	17.27	**23.20**	18.26	27.22
2	25.52	**19.14**	**19.14**	16.53	**23.28**	30.11
3	31.24	20.94	17.09	19.67	22.69	**29.21**
4	21.46	**15.00**	14.79	**17.32**	22.97	24.28
5	20.04	20.21	**11.06**	18.21	**22.44**	25.25
6	**19.88**	**13.52**	**16.24**	**16.57**	20.88	**29.94**
Average	24.31	18.87	14.27	18.58	21.75	27.67
(b)						
1	25.62	26.73	24.05	**26.71**	30.42	35.19
2	22.73	**27.90**	**27.01**	25.14	**31.20**	28.98
3	27.70	23.14	27.98	26.95	26.36	**32.50**
4	24.55	**21.65**	26.59	**22.94**	29.19	38.08
5	22.23	27.58	**27.57**	21.62	**25.65**	33.89
6	**29.82**	**25.52**	**25.81**	**26.33**	30.82	**34.03**
Average	25.44	25.42	26.50	24.95	28.94	33.78

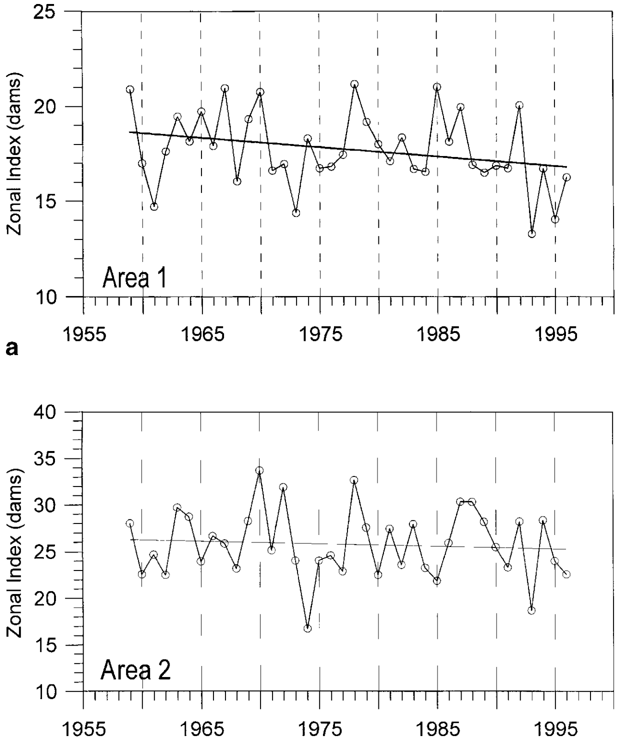

Fig. 5. Seasonal average zonal index (Zi_m) of the high area burned months May, June, and July for 1959 to 1996 and linear trend for (**a**) Area 1 and (**b**) Area 2

August and September. There are no obvious relationships between Zi_m and synoptic type for Area 2.

Figure 5a and 5b show the calculated average Zi_m for Area 1 and Area 2, respectively for the high area burned months May, June, and July for 1959 to 1996. Area 1 Zi_m (Fig. 5a) is calculated over a region of normally weak troughing and strong ridging where flow at 500 hPa is normally meridional. Area 2 Zi_m (Fig. 5b) is calculated over a region of normally strong troughing where flow at 500 hPa is normally zonal. While there are no identifiable trends in the Area 2 index, the Area 1 index is declining with a tendency to more meridional flow through the duration of the period of analysis. Total area burned for each area is compared with the calculated Zi_m for the May, June, July period using Spearman rank correlation. For Area 1 total area burned and Area 1 Zi_m, $r = 0.43$, and for Area 2 total area burned and Area 1 Zi_m, $r = 0.48$. Both relationships are significant at $\propto = 0.001$ or better. No statistical relationship is found with Area 2 fire and Area 2 Zi_m.

5. Discussion

This analysis has demonstrated that in all regions of Canada, especially in western and central areas, monthly periods of high area burned are associated with synoptic types with mid-tropospheric ridging in the proximity of the affected region and high meridional flow, or "low" index, over northern and western North America. During these periods, 500 hPa circulation over northern and western North America is more meridional than normal with an amplification and northward displacement of the continental ridge and a deeper west coast trough and weak or displaced CPT. Additionally, the entire hemispheric flow at mid-latitudes is more meridional than normal (Skinner et al., 1999). Under these conditions, the jet stream is displaced well to the north and often splits with a southern arm across the continental U.S.A. As a result, moisture-bearing systems are deflected well north and south of the affected regions. This is accompanied by high pressure subsidence with surface evaporation and thus dry conditions on a large regional basis. This configuration can dominate the affected region for extended periods of several weeks to months.

Average occurrence of a monthly synoptic type associated with very large area burned over several ecozones is approximately 18% of the years over the period 1959 to 1996, or about one in every five years. The associated monthly synoptic types are large-scale in nature, extend over at least half the continent, and have a very similar pattern during spring and early summer (April to July) – highly meridional flow at 500 hPa (upper blocking) characterized by eastward extension of anomalous heights and deeper than normal west coast trough and weaker, or displaced CPT. Other monthly synoptic types are smaller in spatial scale and are associated with secondary patterns of large area burned on regional levels of one to two ecozones. The identified synoptic types are critically important to the development of drier than normal surface conditions for extended periods of time. The persistence of these types can extend beyond the time frame of one month, and is not restricted to the calendar month. On the other hand, it is possible that more than one synoptic 500 hPa pattern may occur in any given calendar month which could confound the classification. It is also possible that area burned can be greatly influenced over time periods much less than a month, giving rise to variability in the analysis. The largest areas burned during the main fire (May to August) season occur in the western Boreal and Taiga ecozones – the Taiga Plains, Taiga Shield West, Boreal Shield West, and Boreal Plains. The persistence of the identified synoptic types associated with large fire and the fact that much of the area burned occurs in relatively few months may enable the ability to forecast future fire danger.

The lowest Zi_m values calculated for Area 1 are associated with the highest areas burned in Area 1 for the months April to July. There is no association between Zi_m values calculated for Area 2 and area burned in Area 2. However, significant statistical relationships are found between Area 1 Zi_m and both total area burned in both Area 1 and Area 2. This indicates the relationship between atmospheric flow over central and western Canada and resulting surface conditions downstream. A temporal analysis of the zonal index (Zi_m) since 1959 identifies increasing meridional flow over western and northwestern Canada but no change over eastern Canada. This is in keeping with the identified increase in 500 hPa heights over the same period in a previous study for western and north-western Canada (Skinner et al., 1999). It is also consistent with the surface warming observed in the western half of Canada in recent decades, in general, and in NW Canada in summer, in particular (Skinner and Gullett, 1993).

The identified large-scale synoptic types associated with large area burned are critically located with respect to the movement of moist air to an affected region and thus to the development of regional surface moisture stress during summer. They can ultimately affect large regions and impact the potential for wildland fire severity. It is important to concentrate on these clusters and their varying magnitudes from non-severe to severe fire seasons for a more accurate assessment of future fire regimes under changing climatic conditions.

6. Summary

This study represents an extension of a previous study (Skinner et al., 1999) to identify and better understand the links between atmospheric circulation anomalies in the mid-troposphere and wildland fire severity in Canada on finer spatial and temporal scales. It is based on the analysis of the improved spatial and temporal resolution of the Canadian Large Fire Database (LFDB) in conjunction with monthly 500 hPa height data over a northern North American study region.

Monthly 500 hPa synoptic types are objectively determined and relationships between synoptic types and spatial patterns of large fire occurrence are examined at the ecozone level. By far, the largest areas burned during the main fire (May to August) season occur in the western Boreal and Taiga ecozones – the Taiga Plains, Taiga Shield West, Boreal Shield West and Boreal Plains. All are associated with synoptic types that occur often, about 18% of the time, or one year in five. The associated large-scale synoptic types are characterized by eastward extension of anomalous heights and deeper than normal west coast trough and weaker, or displaced CPT. Secondary, more regional, synoptic types are related to large area burned at regional levels.

Monthly burned areas are also analysed temporally, in conjunction with a calculated monthly zonal index (Zi_m). For western Canada, high area burned is associated with synoptic types with mid-tropospheric ridging in the proximity of the affected region and low Zi_m with weak westerlies and strong meridional flow over western Canada (Area 1). For eastern Canada, high area burned is associated with synoptic types with mid-tropospheric ridging in the proximity of the affected region and low Zi_m with weak westerlies and strong meridional flow also over western Canada (Area 1).

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