Development of large vortices on prescribed fires

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A detailed set of data has been compiled on large fire whirlwinds occurring on prescribed burns conducted in Ontario. There appear to be two types of such whirlwinds: one occurs in pairs on the leeward side of the convection column and the other is created after the entire convection column begins to rotate. The second type occurs in association with very intense fires that may be described as fire storms. Fire whirlwind occurrence appears to be related principally to meteorological conditions in which wind speeds are less than 10 km/h, to the stability of the atmosphere up to 3000 m altitude, and to conditions where the amount of energy released from the fire is high. The roles of atmospheric stability, rate of energy release from the fire, and ignition pattern in the development of whirlwinds require further study.

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Des données détaillées ont été réunis sur les gros tourbillons de feu qui se forment au cours de brûlages dirigés en Ontario. Il semble qu'il en existe deux types : ceux qui se produisent en double sous le vent du foyer central et ceux qui sont créés après que la colonne de convection a commencé à tourner. Ceux du deuxième type sont associés à des incendies très intenses qui peuvent être décrits comme des incendies tornades. Les tourbillons de feu semblent principalement se produire lorsque la vitesse des vents est inférieure à 10 km/h, que l'atmosphère est stable jusqu'à 3000 m et que la quantité d'énergie libérée par l'incendie est élevée. Le rôle de la stabilité atmosphérique, de la quantité d'énergie dégagée par l'incendie et du patron d'allumage dans le développement de tourbillons exigera des études plus approfondies.

Introduction

Erratic fire behavior on prescribed burns is undesirable because of the increased risk that the fire will escape and that there will be safety threats to on-site fire personnel. Included in this category of behavior are fire whirlwinds. Although small whirlwinds up to 5 m in height have always been common, recent occurrences of fire whirlwinds up to 400 m in diameter and several thousand metres in height (Fig. 1) have been documented and have caused some concern to fire managers responsible for conducting prescribed burns for the Ontario Ministry of Natural Resources (OMNR). These whirlwinds are well defined by smoke generated by the burns.

Intense atmospheric vortices on or near fires have been observed often in the past. Intense whirlwinds have been associated with an oil refinery fire (Hissong 1926), volcanic eruptions (Thorarinsson and Vonnegut 1964), burning cities (Ebert 1963; Soma and Suda 1977), the Météotron experiment (Dessens 1962; Church et al. 1980; Church and Snow 1985), and forest fires and prescribed fires (Countryman 1964, 1971; Graham 1952, 1957; Haines and Updike 1971; Pirsko et al. 1965). The study of fire whirlwinds has led to some laboratory investigations (Byram and Martin 1962, 1970; Emmons and Ying 1967).

The occurrence of fire whirlwinds at prescribed fires conducted in Ontario in 1986 and 1987 (Table 1) has become quite alarming to provincial officials. Our interest in vortex development began as we were observing and monitoring fire behavior on selected OMNR prescribed burns in 1986 as part of a Forestry Canada (formerly the Canadian Forestry Service) effort in prescribed fire research. On some of the burns, spectacular vortex development was observed and recorded.

Although a great deal of information has been gathered on fire whirlwinds through field and laboratory studies, many mysteries remain; we hope to explain some of these in this paper and to identify other areas that require further investigation. We were able to create a comprehensive data base on the occurrence of the fire whirlwinds as well as associated weather and fuel conditions during these burns. With this information, we will discuss possible mechanisms of fire whirlwind generation.

Prescribed burning in Ontario

Over the past decade, the area covered by OMNR's prescribed fire program has increased from 2471 ha (16 fires) in 1980 to 14 323 ha (58 fires) in 1986 (Kane and Gagnon 1987). These burns are often quite large; for example, the Zig Zag prescribed burn covered 1543 ha, and ignition was completed in just under 4 h (McRae and Stocks 1987). The purpose of conducting these prescribed burns is to reduce woody logging residue and facilitate planting of new trees in forest-renewal programs.

Prescribed burns are planned and carried out by OMNR at a district level, in cooperation with the paper or logging company on whose Forest Management Agreement area the burning site is located. Planning for these prescribed burns follows the procedures contained in the OMNR Prescribed Burn Planning Manual (Ontario Ministry of Natural Resources 1987). Ignition of most burns is from the air with either the

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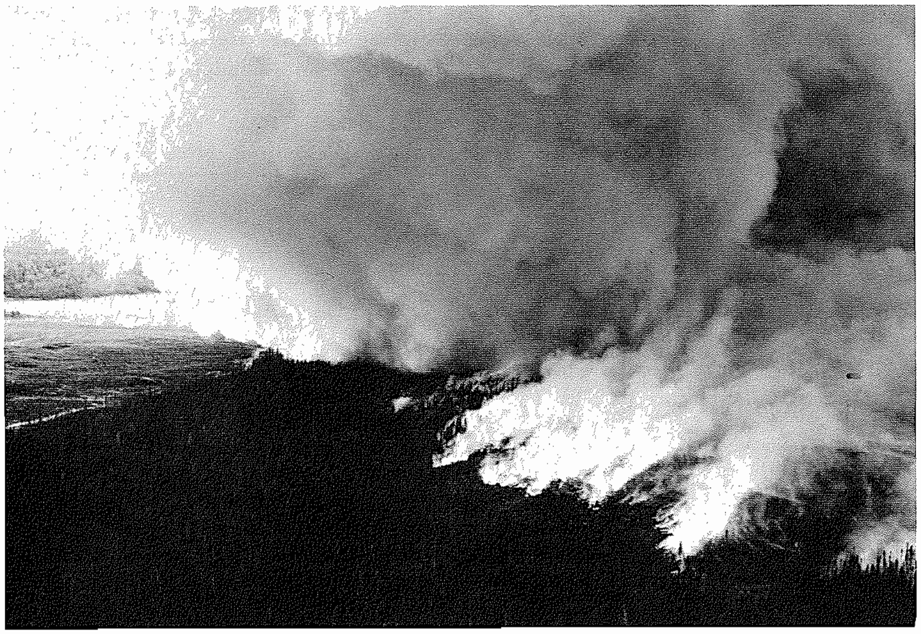

FIG. 1. A large vortex approximately 400 m in diameter travelling through a black spruce stand shortly after the vortex exited from the 1986 Garibaldi prescribed burn in Ontario.

Ontario aerial ignition device (the OAID or Ping-Pong ball machine), which is mounted inside a helicopter and dispenses potassium permanganate - ethylene glycol incendiaries (Lait and Muraro 1979), or a helitorch (a flying drip torch) (Mutch 1984), which is slung below the helicopter. Ignition by means of these two devices, though much quicker than ignition by hand, results in two quite different types of fire behavior. The OAID produces a point-source ignition of approximately 5 cm in diameter and takes approximately 23 min[1] to reach the steady-state fire spread rates observed by Stocks and Walker (1972) without any fuel interruptions or other fire interactions. The helitorch drops a gelled gas, which produces a line ignition that quickly reaches steady-state spread rates (Cheney 1981; Johansen 1987).

In theory the helitorch should be capable of producing greater rates of energy release than the OAID. Rate of spread is important in the determination of frontal fire (fire line) intensity (I, in kilowatts per metre) (Byram 1959), since

$$[1] \quad I = Hwr$$

where H is the low heat of combustion (kJ/kg), w is the mass of fuel consumed in the active flaming zone per unit area (kg/m^2), and r is the rate of spread (m/s). Calculation of total energy release rates (kW) depends on the energy releases from two stages of combustion: flaming (frontal fire intensity) and glowing (McRae and Stocks 1987). The role of r in the determination of frontal fire intensity and its relationship with total energy release underline the critical importance of the ignition technique chosen.

Ignition patterns, i.e., the patterns in which the prescribed fire is set, play an important role in elucidating the behavior of prescribed fires. A number of techniques can be used (Merrill and Alexander 1987), but only two are used regularly in Ontario. Center-fire ignition involves setting fires in a concentrated area to create a strong central convection column and setting additional fires later around the original ignition area. The new fires are drawn towards the convection column because of the development of indrafts. The other common ignition technique is the use of multiple-strip head fires. In this method, a series of successive parallel fires is set in strips in an upwind direction, so that each one burns into the previously ignited strip. The two methods produce different convection-column dynamics, and the strip head fire appears to promote whirlwind development. This process will be explained later in detail.

Data collection

After our first experience with the large fire whirlwinds at the 1986 Garibaldi prescribed burn (Table 1), we found that our sighting was not a unique occurrence. Whirlwinds were observed on a number of burns that year, and several were reported in 1987 by Forestry Canada and OMNR personnel. At least 20 prescribed burns are known to have had vortex development (Table 1). We also tried to obtain, as controls, a set of prescribed burns on which no fire whirlwinds were observed (Table 2). However, although vortices were not reported on a particular burn, this does not mean that they did not occur. Whirlwinds may have been missed because observers were absent from the leeward side of the burn or because the vortices occurred within the burn. Because of this uncertainty, it was impossible to include many fires in Table 2; we listed only seven burns at which Forest Fire Research Unit personnel from Forestry Canada, Ontario Region, were present for the purpose of verification.

Tables 1 and 2 also show the type and pattern of ignition used on the burns. In addition, fuel consumption (Table 3) was measured on all burns by means of the line-intersect fuel sampling technique described by McRae et al. (1979). The data collected at that time included on-site weather information, obained before and during burning, which was used to calculate the fuel moisture codes and fire behavior indices of the Canadian Forest Fire Weather Index (FWI)

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[1] D.J. McRae. 1990. Point-source fire growth in jack pine slash. Manuscript in preparation.

TABLE 1. Fire whirlwind and behavior information for prescribed burns with vortex development

Prescribed burn	Date (d-m-y)	Size (ha)	Type of vortex[a]	Type of ignition[b]	Ignition time[c]	Ignition patterns[d]	Whirlwind		Time of whirlwind sightings[ce]
							Diam. (m)	Visible track length (km)	
Amesdale	22-07-86	256	I	Torch	18:01–20:10	C, SH	1	—	18:15–18:41
Black Bay	27-07-87	955	I	Torch	13:25–17:30	SH	7	—	14:05–14:50
Careu Twp	09-07-87	178	I	Torch	13:03–14:52	C, SH	100	—	←14:11–14:12
Chill Lake	26-07-87	314	I	Torch	16:00–17:30	C	—	—	16:17, 16:27, 16:37
Copperfield	09-08-87	1255	II	Torch	14:47–18:03	SH	400	—	15:09–17:02
Denton	18-08-82	314	I	OAID	17:46–20:30	C	—	—	—
Dumbbell	28-07-87	700	I	OAID	16:53–20:50	SH	—	—	17:24
Garibaldi	25-07-84	309	II	OAID	14:43–15:00	C, SH	—	—	—
Garibaldi	22-08-86	955	II	Torch	12:53–14:53	SH	400	1, 4	13:41→
Garibaldi	30-07-87	872	II	Torch	14:44–19:03	SH	300	—	15:13
Gurney	30-07-86	428	I	Torch	14:12–16:30	SH	—	—	—
Hardiman	28-08-87	323	II	Torch	13:40–16:45	SH	—	1	←15:20–15:28→
Horwood	01-08-87	1100	I	Torch	13:45–18:46	SH	200	—	14:00–14:26
Kenogaming	26-07-86	520	I	Torch	14:44–19:45	SH	—	—	—
Pontiac	14-08-87	208	II	OAID	15:45–17:12	SH	—	—	16:10, 16:55, 17:10
Root River	29-06-86	49	II	OAID	17:00–18:00	SH	10	—	17:10–18:10
Sunshine	30-08-85	625	I	Torch	14:30–18:00	C	200	—	14:36, 16:14, 17:00
Temagami	19-08-86	485	I	OAID	16:27–19:51	C	2	—	16:37–16:52
Thomas	22-08-86	455	II	Torch	12:50–15:58	SH	—	—	—
Twp 238	07-08-86	755	II	Torch	13:47–17:28	SH	—	—	16:30–17:00, 17:30

[a] Vortex types without any rotation of the convection column have been categorized as type I fire whirlwinds; those associated with rotation of the convection column have been classified as type II whirlwinds.
[b] OAID, Ontario aerial ignition device (Ping-Pong ball machine); torch, aerial helitorch slung below a helicopter.
[c] Eastern daylight time.
[d] C, center fire; SH, strip head fire.
[e] Arrows indicate that fire whirlwinds were also present before or after the recorded observation times.

TABLE 2. Fire behavior information on selected prescribed burns with no vortex development

Prescribed burn	Date (d-m-y)	Size (ha)	Type of ignition[a]	Ignition time[b]	Ignition patterns[c]
Byng Twp	26-07-86	414	Torch	14:53–17:30	SH
Charters-A	13-07-83	280	OAID	16:05–20:00	C, SH
Charters-B	12-08-83	480	OAID	15:05–20:00	C
English	25-08-83	445	OAID	18:00–20:30	C, SH
Garibaldi	11-08-83	288	OAID	19:42–21:30	C, SH
Miramachi	13-06-83	83	OAID	20:00–21:00	C
Zig Zag	23-07-86	1543	Torch, OAID	14:46–18:25	P, SH

[a] OAID, Ontario aerial ignition device (Ping-Pong ball machine); torch, aerial helitorch slung below a helicopter.
[b] Eastern daylight time.
[c] C, center fire; SH, strip head fire; P, perimeter fire.

System (Canadian Forestry Service 1984; Van Wagner 1987) (Table 4). The FWI System provides a method of rating fire danger with values that increase as the severity of fire weather worsens; the system incorporates three classes of forest fuel moisture contents and three components that represent the amount of available fuel, fire rate of spread, and frontal fire intensity. Fuel and weather data were easily obtained since collection of this data is required on all prescribed burns conducted by OMNR under its prescribed burning policy (Ontario Ministry of Natural Resources 1987).

At the request of the fire boss, an OMNR weather technician may be stationed on the burn to provide on-site weather briefings. These technicians are equipped to carry out minisonde and pilot balloon ascents to ascertain atmospheric stability and wind conditions above the ground. This information was available for some of the burns (Table 4) and provided valuable information about atmospheric conditions over the burn site (Table 5).

Convection-column heights were measured throughout the burns attended by Forestry Canada personnel. A single theodolite, positioned at right angles to the direction of drift of the smoke, was used.

When available, photographic evidence was gathered by fire personnel to help describe the vortex. Those burns at which Forestry Canada personnel were present were documented with color slides and videotapes. On the Hardiman prescribed burn conducted in 1987, a unique opportunity presented itself. We were able to obtain a military-specification infrared camera coupled to a digitizer–analyzer,

TABLE 3. Fuel-consumption data recorded for all prescribed burns in the present study

Prescribed burn	Date (d-m-y)	0–6.9 cm slash size class[a] Preburn loads (kg/m^2)	0–6.9 cm slash size class[a] Consumption (%)	≥7.0 cm slash size class[a] Preburn loads (kg/m^2)	≥7.0 cm slash size class[a] Consumption (%)	Duff consumption[b] (kg/m^2)	Total consumption (kg/m^2)
Amesdale	22-07-86	2.0	66.7	4.8	36.5	2.6	5.7
Black Bay	27-07-87	3.1	81.3	3.5	35.3	3.6	7.4
Byng Twp	26-07-86	3.2	79.8	7.8	25.4	1.9	6.4
Careu Twp	09-07-87	1.4	86.0	1.9	45.0	8.4	10.5
Charters-A	13-07-83	1.8	98.0	6.4	52.6	6.3	11.4
Charters-B	12-08-83	2.5	90.7	6.3	34.4	3.5	7.9
Chill Lake	26-07-87	3.6	85.0	6.3	54.0	6.1	12.6
Copperfield	09-08-87	2.2	98.4	8.7	41.9	5.3	11.1
Denton	18-08-82	1.6	81.3	3.5	34.3	3.3	5.8
Dumbbell	28-07-87	1.6	59.0	4.9	30.0	1.1	3.5
English	25-08-83	2.2	92.2	6.3	57.0	3.2	8.8
Garibaldi	11-08-83	1.8	93.0	5.9	46.0	2.4	6.8
Garibaldi	25-08-84	1.7	85.9	5.3	31.3	1.1	4.2
Garibaldi	22-08-86	1.4	90.0	3.3	44.0	3.2	5.9
Garibaldi	30-07-87	1.9	96.1	6.2	56.4	3.3	8.6
Gurney	30-07-86	2.3	68.0	3.2	21.0	1.7	3.9
Hardiman	28-08-87	1.8	82.0	2.2	28.0	2.6	4.7
Horwood	01-08-87	1.9	88.4	4.4	39.2	1.7	5.1
Kenogaming	26-07-86	1.8	45.0	4.5	34.0	0.7	3.0
Miramachi	13-06-83	1.3	87.8	3.8	48.6	2.4	5.4
Pontiac	14-08-87	2.2	79.4	7.5	25.0	6.9	10.5
Root River	29-06-86	4.1	83.7	2.7	33.3	2.1	6.4
Sunshine	30-08-85	2.0	72.7	3.4	24.3	2.8	5.1
Temagami	19-08-86	2.9	75.3	4.2	51.1	4.6	8.9
Thomas	22-08-86	2.6	71.0	6.1	34.0	1.4	5.3
Twp 238	07-08-86	1.7	79.3	4.5	27.3	7.1	9.7
Zig Zag	23-07-86	1.8	87.0	3.9	39.0	2.6	5.7

[a] Slash fuels comprise all downed woody logging residue from forest harvesting.

[b] Duff consumption may include the L, F, and H layers of the forest floor, depending on the depth of burn.

with imagery recorded directly on videotape for real-time observation of the fire (Ogilvie 1988). During a portion of this tape, a large vortex that left a ground track 1 km long was filmed.

Vortex observations

Table 1 contains data from 20 prescribed burns on which fire whirlwinds developed and indicates the common occurrence of this phenomenon. The majority of these vortices occurred during two recent burning seasons (1986 and 1987). Several of these vortices were spectacular in both size and strength and deserve a more detailed description. The 1986 Garibaldi prescribed burn (955 ha), for example, had a very fast rate of burning (477.5 ha/h) and an estimated peak energy release of 95.3×10^6 kW (McRae and Stocks 1987). Its convection column reached a height of 5123 m, and three large vortices up to 400 m in diameter (Fig. 1), associated with a strong rotation of the convection column, were documented on the perimeter of the burn. These vortices reached well into the upper portions of the convection column. The senior author, in a helicopter hovering over the burn, observed standing trees being ripped out of the ground and lifted upwards by whirlwinds that were located at the perimeter of the prescribed burns. Although vortex development can usually be distinguished by the thunderous roar that accompanies it, the volume of the sound and its duration (2 h) amazed fire personnel. After the burn, examination revealed two vortex tracks, 1 and 4 km long (Fig. 2). The vortices that created these tracks had removed all large-diameter slash as well as the forest-floor material (duff), exposing the bare mineral soil underneath. Large pieces of slash had been driven into the ground much like spears. The largest of these pieces was 4 m long and 20 cm in diameter, and its blunt end was driven 45 cm into the ground (a sandy soil).

The convection column of the 323-ha Hardiman prescribed burn began rotating midway through the fire. Although no vortices were observed by personnel during the fire, three areas in which whirlwinds had occurred were noted in postburn examinations. These areas, like those on the Garibaldi prescribed burn, were devoid of forest-floor material and (or) woody slash residue. An infrared camera that met military specifications was used to record fire behavior on this burn and documented the location and movement of the largest whirlwind. The vortex developed well inside the burn and left a 1 km long track that led towards the perimeter. Although the vortex did not develop on the leeward side of the burn (on the perimeter), it did develop on the leeward side of a strong convection column that became established during the latter part of the burn.

A stationary vortex, whose upper portions were attached to the strongly rotating but bent-over smoke column, was observed outside of the Pontiac prescribed burn (208 ha). A postburn survey of the area revealed no evidence that the vortex had migrated from the burn area since no burn debris

TABLE 4. Fire weather and fire danger ratings associated with all prescribed burns in the present study

Prescribed burn	Date (d-m-y)	Temp. (°C)	Relative humidity (%)	Wind speed (km/h)	Cloud cover (%)	Canadian Forest Fire Weather Index System[a]					
						FFMC	DMC	DC	ISI	BUI	FWI
Amesdale	22-07-86	26.3	29	4.2	0	91	23	163	5.9	34	12
Black Bay	27-07-87	25.9	36	13.0	20	89	15	324	6.9	26	12
Byng Twp[b]	26-08-86	26.1	46	8.8	0	82	21	273	2.0	35	5
Careu Twp	09-07-87	24.0	64	3.0	100	88	24	310	3.7	41	9
Charters-A	13-07-83	26.0	44	15.0	0	90	26	205	9.0	40	14
Charters-B	12-08-83	23.0	38	4.0	20	90	20	194	5.0	31	10
Chill Lake	26-07-87	22.2	37	7.1	10	90	12	188	5.9	21	9
Copperfield	09-08-87	27.3	50	7.0	10	88	26	264	4.5	42	11
Denton	18-08-82	22.0	54	0.0	30	86	23	270	2.5	38	7
Dumbbell[b]	28-07-87	21.7	60	5.0	80	86	14	295	3.0	25	6
English	25-08-83	25.0	59	7.0	20	86	17	249	4.0	29	7
Garibaldi	11-08-83	21.0	51	10.0	0	84	14	235	3.0	24	6
Garibaldi	25-07-84	23.5	40	8.0	60	89	20	127	5.5	29	11
Garibaldi[b]	22-08-86	16.0	51	2.0	100	88	24	91	4.0	37	10
Garibaldi[b]	30-07-87	17.0	59	7.0	30	87	22	215	4.1	35	9
Gurney[b]	30-07-86	31.0	36	0.0	0	92	32	320	5.4	52	14
Hardiman	28-08-87	19.0	44	5.0	0	88	15	257	4.1	27	8
Horwood[b]	01-08-87	26.0	47	4.0	10	89	31	186	4.6	44	11
Kenogaming[b]	26-07-86	23.8	48	2.0	30	81	21	300	1.4	36	3
Miramachi	13-06-83	31.0	43	6.0	0	90	23	77	6.0	25	10
Pontiac	14-08-87	28.3	47	7.8	50	90	30	148	6.0	39	14
Root River	29-06-86	20.0	38	2.7	10	89	20	216	4.2	33	9
Sunshine[b]	30-08-85	22.8	29	2.9	10	90	28	108	5.0	34	10
Temagami	19-08-86	22.3	41	10.0	0	88	21	284	6.1	35	13
Thomas[b]	22-08-86	16.0	45	6.0	100	87	19	91	4.0	25	7
Twp 238[b]	07-08-86	24.4	42	6.8	10	83	24	269	1.8	39	5
Zig Zag[b]	23-07-86	28.9	40	11.7	10	87	26	289	7.0	42	15

[a] FFMC, Fine Fuel Moisture Code; DMC, Duff Moisture Code; DC, Drought Code; ISI, Initial Spread Index; BUI, Buildup Index; FWI, Fire Weather Index. Further component definitions of the Fire Weather Index System may be found in Canadian Forestry Service (1984). Values represent maxima that occurred during the ignition period.

[b] Minisonde and pilot balloon ascents were carried out to verify atmospheric stability and winds aloft (see Table 5).

was discovered in the area. This was the only vortex in our study that was formed without fire as part of its structure and that remained outside the burn area. In essence, this vortex appears very similar to the tornadoes shown in photographs by Dessens (1962).

The convection column of the 1255-ha Copperfield burn reached a height of 9928 m and produced some precipitation downwind from the burn. Continuous creation of large whirlwinds (200–400 m in diameter) was observed on the leeward perimeter of the fire over a period of 2 h and caused fire-control problems.

In most cases in which fire whirlwinds migrated outside of the prescribed burn perimeter, their lifetime was short. It appears that once the vortices were displaced from the energy of the burn, they quickly dissipated. The exception to this rule was one vortex found on the 1986 Garibaldi burn, in which the intense burning associated with the vortex allowed it to carry (crown) 400 m through a black spruce (*Picea mariana* (Mill.) B.S.P.) stand before breaking up as a result of a lack of fuel when it encountered a previously burned site (Fig. 1). Black spruce is normally fireproof at this time of the year as a result of high foliar moisture content (Van Wagner 1967); however, the strong winds associated with the vortex were sufficient to compensate for the high fuel moisture and to carry the fire through the spruce stand.

Discussion

The observation of a large number of fire whirlwinds has been useful in the production of a detailed data base on which to clarify a number of points about their formation. The first is that fire whirlwinds in Ontario generally occur when low-level winds are light. Only one prescribed burn for which surface wind speeds (anemometer at 10 m) were more than 10 km/h had fire whirlwinds (Table 4). The mean wind speed for burns without fire whirlwinds was 8.9 km/h in comparison with 5.2 km/h for burns with fire whirlwinds. By means of a t-test carried out with statistical software (SAS Institute Inc. 1985), we found that the probability of a greater absolute value of t for the hypothesis that the difference in the means is zero is greater than 0.98. However, our data are biased, as prescribed burns are not usually carried out if wind speeds exceed 20 km/h because of concerns about fire control. Another indicator that wind speeds are low when fire whirlwinds are imminent is the appearance of the convection column. Figure 3 illustrates a smoke column, observed just prior to whirlwind development, that is vertical and clearly defined on the leeward side near the surface of the earth. The lack of tilt of the column indicates that the ambient wind is not strong. Pirsko et al. (1965) discuss the occurrence of a fire whirlwind when the wind speed was over 30 km/h. However, this fire whirlwind was probably the result of wind flowing over a ridge. Fire whirlwinds

TABLE 5. Minisonde ascent data for prescribed burns on which minisonde and pilot balloon ascents were carried out

Prescribed burn	Temp. difference from surface to 1000 m AGL (°C)	Wind speed (km/h)		Wind direction change with height (surface to 1000 m AGL)
		Surface	1000 m AGL	
Byng Twp	−11	9	8	Backing
Dumbbell	−6	5	26	Veering
Garibaldi (22-08-86)[a]	−6	2	16	No change
Garibaldi (30-07-87)[ab]	−9	7	na	na
Gurney	−10	0	12	No change
Horwood	−15	4	30	No change
Kenogaming	−11	2	8	Backing
Sunshine	−17	3	15	Veering
Thomas	−8	6	23	No change
Twp 238	−11	7	5	Backing
Zig Zag	−18	12	13	No change

NOTE: AGL, above ground level.

[a] Numbers in parentheses represent day-month-year.

[b] The balloon ascent was lost in low cloud cover; wind speed was 22 km/h at 500 m, with the wind veering.

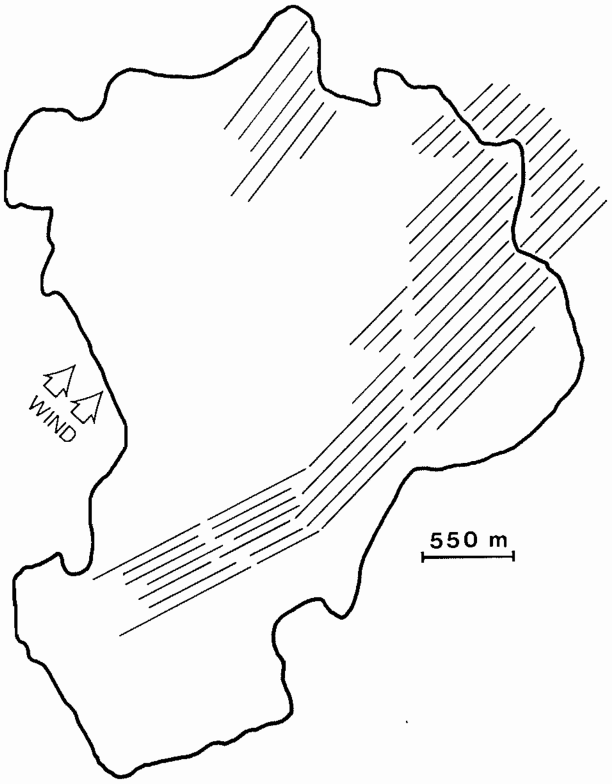

FIG. 2. Location of fire whirlwind activity (hatched area) found on the 1986 Garibaldi prescribed burn.

can occur with higher wind speeds but our limited data suggest that higher wind speeds (>10 km/h) in Ontario, where burn sites are relatively flat, suppress most fire whirlwind activity.

Another issue that we can address is the role of surface temperature, relative humidity, fire weather indices, and the presence of clear skies in the occurrence of fire whirlwinds. With the data from Table 4, we used a *t*-test to determine if there was any difference in the means between the prescribed burns with fire whirlwinds and those without fire whirlwinds. The means were similar for all of the elements of Table 4 except wind speed (as already discussed), temperature, and percent cloud cover. The mean temperature of prescribed burns without fire whirlwinds was higher than that of burns with fire whirlwinds. Also, the mean percent cloud cover associated with prescribed burns without fire whirlwinds was lower than that associated with burns with fire whirlwinds. Differences in means of both temperature and percent cloud cover cannot be explained easily in physical terms. These differences probably stem from the fact that our sample size for prescribed burns without fire whirlwinds was too small; there were only seven observations. From the analysis, there is no clear indication that any of these variables plays a major role in the occurrence of fire whirlwinds. Haines and Updike (1971) state that clear skies provide optimum conditions for formation of fire whirlwinds. Our data did not support this hypothesis; in fact, the most violent whirlwind in our study (Garibaldi-86) occurred on a cloudy day. Obviously, other factors are playing major roles in the formation of fire whirlwinds.

What is not yet clear is the role of a low-level superadiabatic lapse rate in the occurrence of fire whirlwinds. In all the minisonde ascents for prescribed fires both with and without fire whirlwinds, the environmental lapse rate for the lowest 1000 m is usually near the dry adiabatic lapse rate or is superadiabatic[2] (Table 5). Prescribed burns are not usually ignited unless the weather is within the limits prescribed. In Ontario, fine summer weather is usually characterized by an adiabatic lapse rate in the afternoon that is equivalent to the dry adiabatic or superadiabatic rate. Most fire whirlwinds occurred when the environmental lapse rate was dry or superadiabatic, but we believe they could occur with lapse rates other than dry or superadiabatic.

We also believe that production of intense fire whirlwinds is a function of the interaction of the rate of energy release

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[2] The dry adiabatic lapse rate is the rate of decrease of temperature, with height, of a parcel of dry air ascending in the atmosphere without mixing or heat exchange, and is equal to 1°C/100 m. If the environmental lapse rate has a decrease of temperature, with height, that exceeds 1°C/100 m, it is called superadiabatic.

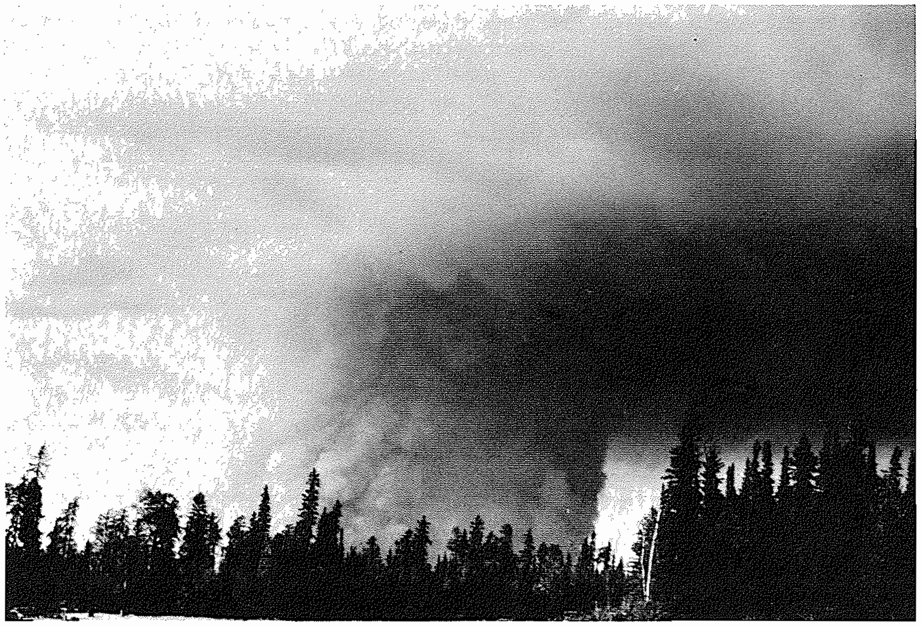

FIG. 3. A view of the development of the steep leeward side of a convection column (right side) just before the occurrence of a fire whirlwind.

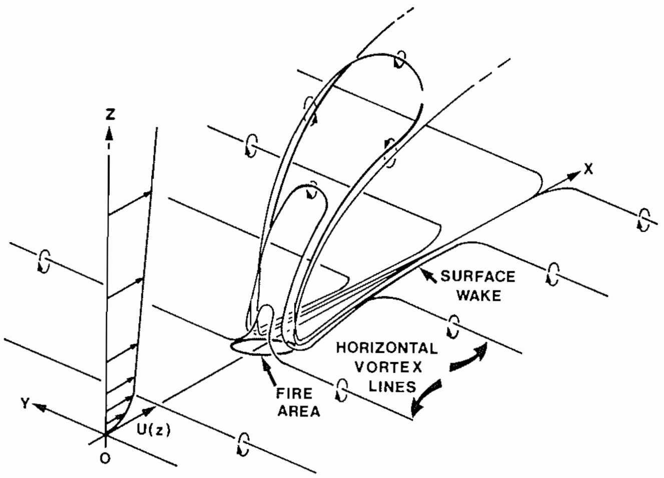

FIG. 4. Rising plume producing loops in otherwise horizontal vortex tubes present in the environmental wind field. This results in a clustering of vortex lines with a strong component parallel to the plume axis along each downward flank. (From Church et al. 1980, reproduced with permission of Bull. Am. Meteorol. Soc. Vol. 61. No. 7. ©1980 The American Meteorological Society.)

and the degree of atmospheric instability. The rotation (vorticity) of the convection column or fire whirlwinds is generated by the buoyancy of the plume, which is a function of the rate of energy release and of atmospheric instability. The buoyant plume indrafts the available background vorticity. This background vorticity can be from either advection of vertical vorticity or the tilting of horizontal vorticity. When the rate of energy release is high, the fire is intense and the inflow of air generated by the convergence of the fire could create horizontal vorticity as a result of the vertical wind-speed shear in the indraft (Fig. 4). Once the vortex tube is advected to the plume it will be stretched by the rising plume, thereby amplifying the magnitude of the vorticity.

Haines and Smith (1987) discuss the role of energy dispersion in the formation of horizontal roll vortices. They found that horizontal vortices developed under extreme burning conditions and felt that substantial energy was required to modify the inflow wind field to allow vortex formation in the plume.

The role of atmospheric instability in the generation of vortices needs to be examined. The degree of atmospheric stability or instability is measured by the lapse rate. The greater the instability of the lower atmosphere, the stronger the buoyancy of the column, and the stronger the resulting updraft. The greater the buoyancy force, the more likely it is that fire whirlwinds will occur. The interaction between atmospheric instability and the rate of energy release from the fire requires further investigation. McRae and Stocks (1987) calculated energy release rates for three prescribed burns (Table 6). Fire whirlwinds were recorded at the Garibaldi and Thomas burns in 1986; Fig. 5 is a plot of height versus temperature for all three burns. The Zig Zag burn, on which no fire whirlwinds were recorded, had higher energy release rates than the Thomas burn and a deeper layer of unstable air than the other burns. Two factors may have contributed to the absence of fire whirlwinds at the Zig Zag burn. First, the wind speeds were observed to be stronger than those reported for the other burns (Table 4). Second, the lack of available vorticity might have been the controlling factor at the Zig Zag burn. The role of the inversion layer at the top of the planetary boundary layer (the layer of atmosphere up to 3 km above the ground) also deserves further study. The height and strength of this inversion may play a role in fire whirlwind development. More data need to be collected before we can comment on this relationship, but the point that we wish to make is that fire whirlwinds can occur under any stability regime if the rate of energy release is sufficiently high.

The role of streamwise vorticity in the development of fire whirlwinds was investigated by examining hodographs

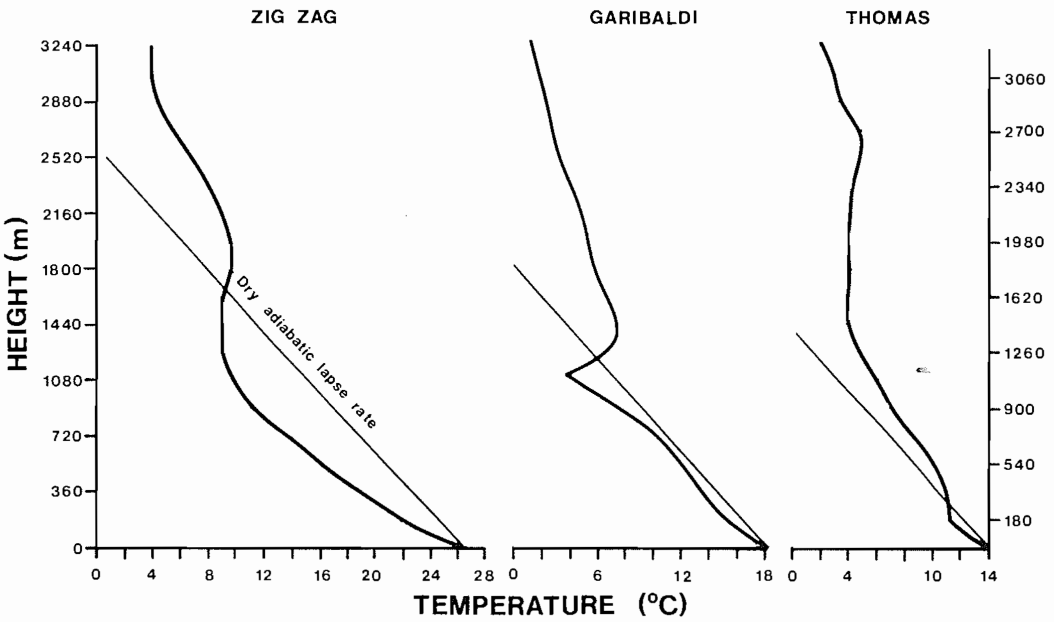

FIG. 5. Vertical temperature profiles for the Zig Zag, 1986 Garibaldi, and Thomas burns (reprinted from McRae and Stocks 1987).

(wind speed and direction as a function of height) from those prescribed burns with minisonde ascents. Streamwise vorticity is associated with the change of wind direction with respect to height. Davies-Jones (1984) showed that streamwise vorticity can play a major role in the origin of the updraft rotation in super-cell thunderstorms. Veering (a change in a clockwise direction) or backing (a change in a counterclockwise direction) of the wind with increasing height is not a requirement for the formation of fire whirlwinds, as whirlwinds were present even when wind direction remained steady with height. In those hodographs in which the wind veered or backed with increasing height, the wind speeds were often light up to a considerable height, so that any vorticity contribution from wind speed would have been small.

The three-dimensional flow field for all the observed vortices is uncertain. There were probably both one- and two-cell vortices. Figure 6 shows the vertical cross-section flow for one- and two-cell vortices. The one-cell vortex is characterized by an updraft at the core of the vortex, whereas the two-cell vortex has a downdraft in the core region and an updraft around the core. From observational evidence, most of the fire whirlwinds in this study appear to be of the one-cell variety, but because of poor visibility it is impossible to know the flow structure for every vortex.

Of unknown importance is the role of ignition techniques and patterns. Ignition plays a role in determining the rate of energy release. Of the two types of ignition, the helitorch is usually responsible for higher energy release rates than OAID as a result of the prominent line ignition by the device, which may give a higher probability of fire whirlwind occurrence. The helitorch allows for easy and faster ignition of the burn area. The increase in the number of observations of fire whirlwinds seems to have coincided with the introduction and major use of the helitorch in Ontario's prescribed burning program that began in 1986.

The multiple-strip head-fire ignition technique develops only a strong indraft on the windward side of the burn, which allows for the development of a strong, well-defined leeward side to the column, where the indrafting process is weak. It is on this leeward side of the column that many of the fire whirlwinds have developed. Countryman (1971) describes how ths might happen when the convection column of the fire acts as a block to the gradient winds. When the wind is split and forced around the column and permitted to come together on the leeward side of the fire, wind shear and eddies are formed next to the column on the leeward side of the fire. These eddies have the potential to develop into fire whirlwinds. Since the convection column remains strong only over the most active portion of the fire (flaming stage of combustion), the column is shifted in time over the burn site as earlier strip head fires burn together and strips set later become more active. This movement of the column means that the leeward side of the active column shifts further into the burn site as the burn progresses. Hence, whirlwinds can develop within the overall burn as time passes. Although it is very easy to see the whirlwinds on the outer perimeter near the beginning of the fire, it is difficult to observe the whirlwinds that develop in the interior of the burn because of the amount of smoke generated; either postburn evidence or expensive infrared obser-

TABLE 6. Energy release rates (flaming and glowing combustion) for three prescribed burns (from McRae and Stocks 1987)

Prescribed burn	Date (d-m-y)	Time since ignition (min)	Total energy release rate (kW × 10^6)
Zig Zag	23-07-86	104	84.3
Garibaldi	22-08-86	49	78.7
		79	72.1
		99	95.3
		132	54.8
Thomas	22-08-86	17	0.2
		88	47.0
		96	63.6
		188	48.4

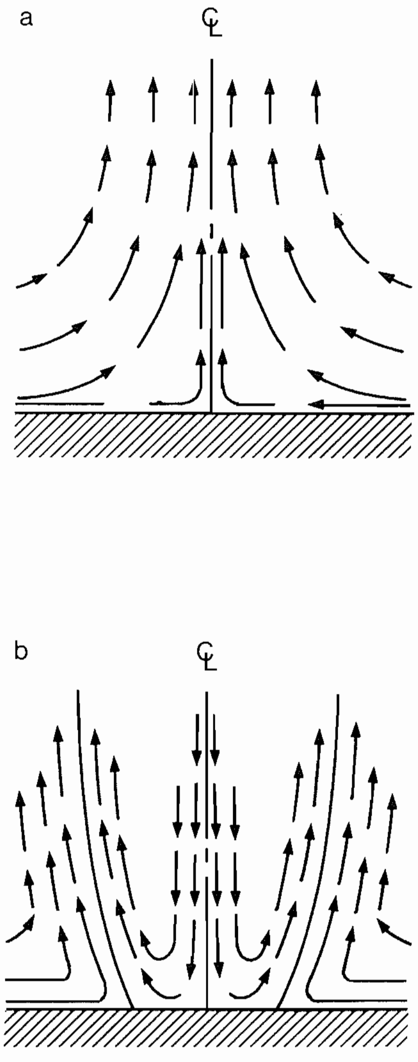

FIG. 6. Flow field for (*a*) one-cell vortex and (*b*) two-cell vortex (adapted from Davies-Jones 1985).

vations are required to clarify their development. Center fires with strong indrafting on all sides produce a burn that has no strong leeward side to the column. To date, no whirlwinds have been observed on center-fire ignitions unless indrafting has not yet begun or has died out during the latter part of the burn. One might imagine that the center-fire technique would lead to more fire whirlwinds by focusing the ambient vorticity into a central column, but the data do not support this (Tables 1 and 2).

The literature suggests that there are a number of fire whirlwind types. We observed two principal types: type I consists of fire whirlwinds formed on the leeward side of the convection column; type II consists of fire whirlwinds formed as the result of rotation of the entire column. Excluded from this classification are whirlwinds of very limited horizontal and vertical extent, such as those with diameters of up to 3 m and heights up to 5 m that are often observed on large fires and are usually of short duration (less than 10–15 s). There may be other types of vortices associated with prescribed fires (e.g., the vortices that occurred near the Pontiac burn). It is likely that the Pontiac vortices were type II vortices that were displaced further downwind

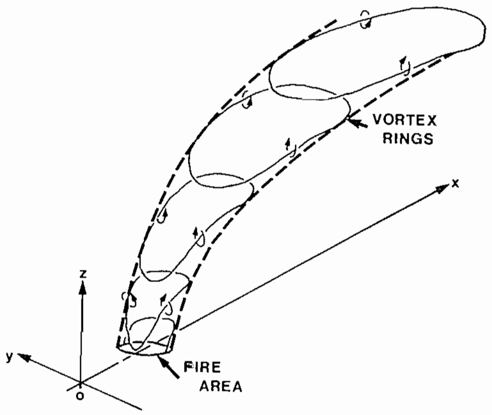

FIG. 7. Production of vorticity within the plume by buoyancy and drag forces. The vortex rings are tilted so that the vorticity field matches the motion field within the plume. This produces a clustering of vortex lines with a strong component parallel to the plume axis along each flank. (From Church et al. 1980, reproduced with permission of Bull. Am. Meteorol. Soc. Vol. 61. No. 7. ©1980 The American Meteorological Society.)

outside the burn area. Further observations and data are required to determine if there are other types of fire whirlwinds. This classification should not be confused with that for the one- and two-cell vortices. Type I and II fire whirlwinds can be one or two cell; the distinction between types I and II is in the mechanism of production.

The type I fire whirlwinds are the result of reorientation of horizontal vortex tubes as shown in Fig. 4 or the interaction of buoyancy and drag forces (Fig. 7); they usually have diameters of 100 m or less but can be quite intense, and can occur in pairs, with the fire whirlwind to the right of the wind direction rotating cyclonically and the whirlwind to the left rotating anticyclonically. Neither rotation appears to be favored over the other. The lack of preference is to be expected at this scale, as the rotation of the earth can be considered negligible. Sinclair (1969) in his study found no clear preference for the rotation of dust devils, a related phenomenon.

The type II fire whirlwind occurs when the entire convection (smoke) column begins to rotate. The diameter of these whirlwinds can be very large (> 100 m). The term fire storm is used to describe very intense fires, and it is on such fires that the type II fire whirlwinds quite often occur. The type II fire whirlwinds probably occur as a result of the stretching of existing vertical vorticity, which is advected from the surrounding regions, or as a result of buoyancy. An audible clue that has been described as a roar like that of a waterfall or freight train, or like peals of thunder, often accompanies type II and occasionally type I fire whirlwinds. The roar can be heard for several kilometres and may last as long as the whirlwind. The fire whirlwinds at the 1986 Garibaldi prescribed burn are an example of a type II fire whirlwind.

Many questions remain about the occurrence of fire whirlwinds. The roles of atmospheric instability and the rate of energy release deserve more scrutiny. As well, the impact of ignition techniques and patterns and the structure of the flow field and vorticity field require further investigation. With additional observations, we hope to develop a model of fire whirlwind occurrence.

Summary

In recent years fire whirlwinds have become common on prescribed burns in Ontario. Whirlwinds occur under a variety of meteorological conditions; however, winds over 10 km/h seem to suppress fire whirlwind activity. Whirlwind occurrence appears to be related to the rate of energy release by the fires as well as the stability of the atmosphere in the 1000 to 3000 m closest to the ground. Two types of fire whirlwinds have been observed: type I whirlwinds usually occur in pairs on the leeward side of the convection column, whereas type II whirlwinds occur when the entire column goes into rotation. Both types of whirlwind present a hazard to the safety of fire-control personnel and both pose problems for the containment of the fire. Because of the many uncertainties that still exist about fire whirlwinds, further investigation is required.

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Byram, G.M. 1959. Combustion of forest fuels. *In* Forest fire: control and use. *Edited by* K.P. Davis. McGraw-Hill, New York. pp. 61–89.

Byram, G.M., and Martin, R.E. 1962. Fire whirlwinds in the laboratory. Fire Control Notes, **23**: 13–17.

______ 1970. The modeling of fire whirlwinds. For. Sci. **16**: 386–399.

Canadian Forestry Service. 1984. Tables for the Canadian Forest Fire Weather Index System. 4th ed. Can. For. Serv. For. Tech. Rep. No. 25.

Cheney, N.P. 1981. Fire behavior. *In* Fire and the Australian biota. *Edited by* A.M. Gill, R.H. Groves, and I.R. Noble. Australian Academy of Science, Canberra. pp. 151–175.

Church, C.R., and Snow, J.T. 1985. Observation of vortices produced by the Météotron. J. Rech. Atmos. **19**: 455–467.

Church, C.R., Snow, J.T., and Dessens, J. 1980. Intense atmospheric vortices associated with a 100 MW fire. Bull. Am. Meteorol. Soc. **61**: 682–694.

Countryman, M. 1964. Mass fire and fire behavior. USDA For. Serv. Res. Pap. PSW-19.

______ 1971. Firewhirls—why, when and where. USDA Forest Service, Washington, DC.

Davies-Jones, R.P. 1984. Streamwise vorticity: the origin of updraft rotation in supercell storms. J. Atmos. Sci. **41**: 2991–3006.

______ 1985. Tornado dynamics. *In* Thunderstorm morphology and dynamics. 2nd ed. *Edited by* E. Kessler. University of Oklahoma, Norman. pp. 197–236.

Dessens, J. 1962. Man-made tornadoes. Nature (London), **193**: 13–14.

Ebert, C.H.V. 1963. Hamburg's firestorm weather. Q. Natl. Fire Prot. Assoc. **57**: 253–260.

Emmons, H.W., and Ying, S.J. 1967. The firewhirl. *In* The 11th Symp. on Combustion, Combustion institute, Pittsburgh, PA. pp. 475–486.

Graham, H.E. 1952. A fire-whirlwind of tornadic violence. Fire Control Notes, **13**: 22–24.

______ 1957. Fire whirlwind formation as favored by topography and upper winds. Fire Control Notes, **18**: 20–24.

Haines, D.A., and Smith, M.C. 1987. Three types of horizontal vortices observed in wildland mass and crown fires. J. Clim. Appl. Meteorol. **26**: 1624–1637.

Haines, D.A., and Updike, G.H. 1971. Fire whirlwind formation over flat terrain. USDA For. Serv. Res. Pap. NC-71.

Hissong, J.E. 1926. Whirlwinds at oil tank fire. San Luis Obispo. Calif. Mon. Weather Rev. **54**: 161–163.

Johansen, R.W. 1987. Ignition patterns and prescribed fire behavior in southern pine stands. Ga. For. Res. Pap. No. 72.

Kane, M., and Gagnon, P.R. 1987. 1986 prescribed burn program summary: province of Ontario. Ontario Ministry of Natural Resources, Aviation and Fire Management Centre, Sault Ste. Marie.

Lait, G.R., and Muraro, S.J. 1979. The PFRC aerial ignition system: mark II. Can. For. Serv. Pac. For. Res. Cent. Inf. Rep. BC-X-167.

McRae, D.J., and Stocks, B.J. 1987. Large-scale convection burning in Ontario. *In* The 9th Conference on Fire and Forest Meteorology, 21–24 Apr. 1987, San Diego. American Meteorological Society, Boston. pp. 23–30.

McRae, D.J., Alexander, M.E., and Stocks, B.J. 1979. Measurement and description of fuels and fire behavior on prescribed burns: a handbook. Can. For. Serv. Great Lakes For. Cent. Inf. Rep. O-X-287.

Merrill, D.F., and Alexander, M.E. 1987. Glossary of forest fire management terms. Natl. Res. Counc. Can. Rep. NRCC 26516.

Mutch, R.W. (*Technical Coordinator*). 1984. Proceedings, Prescribed Fire by Aerial Ignition, 30 Oct. – 1 Nov. 1984, Missoula, MT. Intermountain Fire Council, Missoula, MT.

Ogilvie, C.J. 1988. Hi tech: hot spots. Timberlines, **6**(Spring): 2.

Ontario Ministry of Natural Resources. 1987. Prescribed burn planning manual. Ontario Ministry of Natural Resources, Aviation and Fire Management Centre, Sault Ste. Marie.

Pirsko, A.R., Sergius, L.M., and Hickerson, C.W. 1965. Causes and behaviour of a tornadiac fire-whirlwind. USDA For. Serv. Res. Note PSW-61.

SAS Institute Inc. 1985. SAS user's guide: statistics, version 5. SAS Institute Inc., Cary, NC.

Sinclair, P.C. 1969. General characteristics of dust devils. J. Appl. Meteorol. **8**: 32–45.

Soma, S., and Suda, K. 1977. Fire tornado and its maximum wind speed. United States National Bureau of Standards, Washington, DC. Spec. Publ. No. 470. pp. 123–141.

Stocks, B.J., and Walker, J.D. 1972. Fire behavior and fuel consumption in jack pine slash in Ontario. Can. For. Serv. Great Lakes For. Cent. Inf. Rep. O-X-169.

Thorarinsson, S., and Vonnegut, B. 1964. Whirlwinds produced by the eruption of Surtsey Volcano. Bull. Am. Meteorol. Soc. **45**: 440–444.

Van Wagner, C.E. 1967. Seasonal variation in moisture content of eastern Canadian tree foliage and the possible effect on crown fires. Can. Dep. For. Rur. Dev. For. Br. Publ. No. 1204.

______ 1987. Development and structure of the Canadian Forest Fire Weather Index System. Can. For. Serv. For. Tech. Rep. No. 35.