METEOROLOGICAL FACTORS ASSOCIATED WITH A FIRE WHIRLWIND

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ABSTRACT

A fire lit in scrubland at Pouakani, near Mangakino on 18 January 1974 in the course of land clearance prior to afforestation, unexpectedly gave rise to a violent whirlwind. From the synoptic situation and known meteorological factors, it is concluded that the whirlwind occurred in a situation with low stability and with light winds in a deep layer associated with a "heat low".

INTRODUCTION

On 18 January 1974 New Zealand Forest Products Ltd planned to burn off an area of 392 ha at Pouakani near Mangakino, in the central North Island. The area was one of several being cleared for eventual planting of exotic forest. The area was covered in scrub which had been cut and treated with a desiccant to make it burn more readily. The terrain of the block and vicinity is hilly but not generally rugged though there are some steep sided gullies.

Weather and humidity conditions, as noted by observers on the ground, seemed favourable for the complete burn desired yet conditions were not exceptionally hot or dry. Relative humidity data from nearby places (Fig. 1) that make several reports daily are shown in Table 1. Temperature and humidity data for 18 January 1974 for climatological stations in the area are compared with statistical data for January in Table 2, showing that the day was warm and dry but not exceptionally so.

Lighting was begun near the western end of the block (Fig. 2) by three parties at 1245 NZST. One group lit from the road which passes through the block while the other two groups lit as they moved in opposite directions around the periphery of the block. At the time of first ignition the local wind was light from east of north; the usual practice of burning into wind was followed.

The whirlwind developed (Fig. 2) near the top of a line of small hills. It moved down the hillside trapping the work crew that were igniting from the road; 14 men were injured and a utility vehicle was completely destroyed. The whirlwind then travelled a further distance of approximately 2.5 km in a general northeasterly direction.

A remarkable feature of this whirlwind was that although it was associated with generally intense burning there was an unburnt strip close to or even along the path of the whirlwind (Fig. 2).

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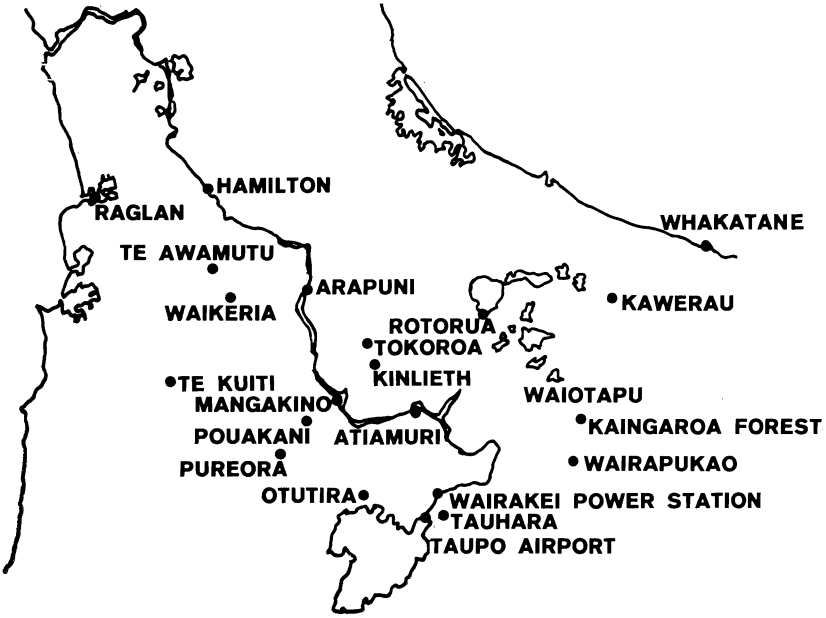


FIG. 1—Locality map, vicinity of Pouakani.

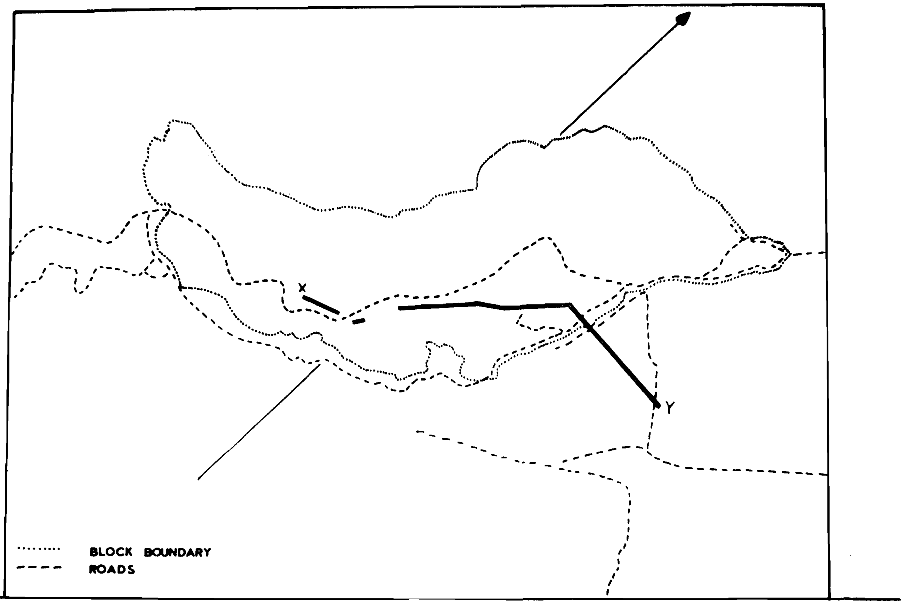


FIG. 2—Map of the block in which the burn took place on 18 January 1974, based on photographs supplied by N.Z. Forest Products Ltd. Approx. scale 1: 36000. The whirlwind began at X. The path, as determined largely from observations of the unburnt strip, is shown by the solid line. Gaps in this line indicate places where the whirlwind seems to have "jumped" across low-lying areas. No trace of the whirlwind was found beyond Y.

TABLE 1—Relative humidity (%) on 18 January 1974

Time (NZST)	Forestry Stations (N.Z. Forest Service) Pureora	Kaingaroa	Wairapukao	Waiotapu	Tauhara	Airports (Ministry of Transport) Taupo	Rotorua	Hamilton
0900	72	61	58	66	70	74	65	65
1000						65	65	
1100						61	54	
1200						54	38	47
1300	58	58	48	47	41	—	48	
1400						47	45	
1500						39	42	45
1600						42	51	
1700							54	

TABLE 2—Data from climatological stations

Station	18 January 1974 Maximum Temp.	9 a.m. Relative Humidity %	Mean Monthly Maximum °C	January Statistical Data Mean Daily Maximum °C	Average 9 a.m. Relative Humidity %	Years of Record
Arapuni	27.5	68	29.4	24.7	76	1951-1970
Atiamuri	27.3	62	—	—	—	—
Kawerau	27.4	49	30.8	25.5	68	1954-1970
Kinleith	24.3	71	—	—	—	—
Otutira	23.7	72	—	—	—	—
Pureora	24.7	72	25.9	20.6	79	1947-1970
Taupo	28.3	74	28.7	23.4	73	1949-1970
Tokoroa	25.0	70	—	—	—	—
Waikeria	26.6	62	28.3	24.2	75	1957-1970
Wairakei Power Station	26.0	69	29.7	23.8	73	1951-1970
Wairakei Soil Conserv. Stn.	25.9	79	—	—	—	—
Wairapukao	25.4	58	29.6	23.4	74	1951-1970

Dashes indicate statistics unavailable

PREVIOUS STUDIES

Byram (1954) used the term "blow up" to refer to a fire that "burns with an intensity that seems far out of proportion to apparent burning conditions". Large fire whirlwinds are one class of such fires. From empirical studies Byram concluded that blow up occurred when the atmosphere was unstable (i.e. convective motion could take place readily) and when the wind either decreased with height above the fire or alternatively increased for a few hundred feet above the fire and then decreased. A theory relating blow up to these wind profiles was also proposed (Byram, 1959). An alternative theory has been suggested by the author (Steiner, 1976).

Whittingham (1964), and Kiil and Grigel (1969) have reported cases of fires burning out of control accompanied by whirlwinds. The wind profile above the fires in these cases was as described by Byram. However not all fire whirlwinds are associated with these profiles. Graham (1955) found little relationship between Byram's wind profiles and whirlwinds associated with forest fires in the northwestern U.S.A. He found that the most common feature of the 28 whirlwind days studied was that most whirlwinds occurred on lee slopes.

Theoretical Considerations

(a) *Atmospheric Stability*

The heated air parcels from a fire would rise with their temperature decreasing at a rate of 9.77°C/km if they did not mix with their environment. In fact mixing always occurs so the rate of decrease of temperature with height differs from this value; it exceeds this value in at least the lower layers. In the part of the rising air column where the column is warmer than its surroundings, conversion of potential energy (due to the buoyancy of the heated air parcels) to kinetic energy takes place. The conversion to kinetic energy is thus dependent on the depth of the region of excess column temperature and on the magnitude of the excess temperature within this depth. The conversion will thus be large if the ambient air temperature decreases rapidly with height over a considerable depth. Under these conditions the air is said to be unstable. The kinetic energy produced is shared by the whole convective circulation, thus causing stronger intake of air into the fire region. Of course the mixing of heated air from the fire with ambient air has a destabilizing effect on the system. If the air is initially unstable a rapid development of the fire's convective circulation can occur immediately.

The importance of stability on fire development is discussed by Davis (1969).

(b) *The Formation of Whirlwinds*

This is discussed in the Appendix. A fuller treatment is that of Morton (1969).

OBSERVATIONS

Weather Conditions on 18 January

Surface Maps

Wind, temperature, dew point, pressure and direction of movement of any low level clouds (bases below 2400 m) at 0900, 1200 and 1500 NZST are shown in Fig. 3. The data come mainly from synoptic stations, i.e. reporting stations relaying current weather data at standard times of observation to forecasting offices. Some additional data from the afforestation areas were obtained from the New Zealand Forest Service and from N.Z. Forest Products Ltd for times up to one hour after those of the rest of the reports.

The synoptic stations in central areas reported fine or partly cloudy weather except that at 1500 Te Kuiti reported overcast skies and rain. Some additional information on the location of rain areas was also obtained at 1030 and 1430 by surveillance radars at Auckland and Ohakea and is shown on Figs. 3a and 3c respectively as hatched areas.

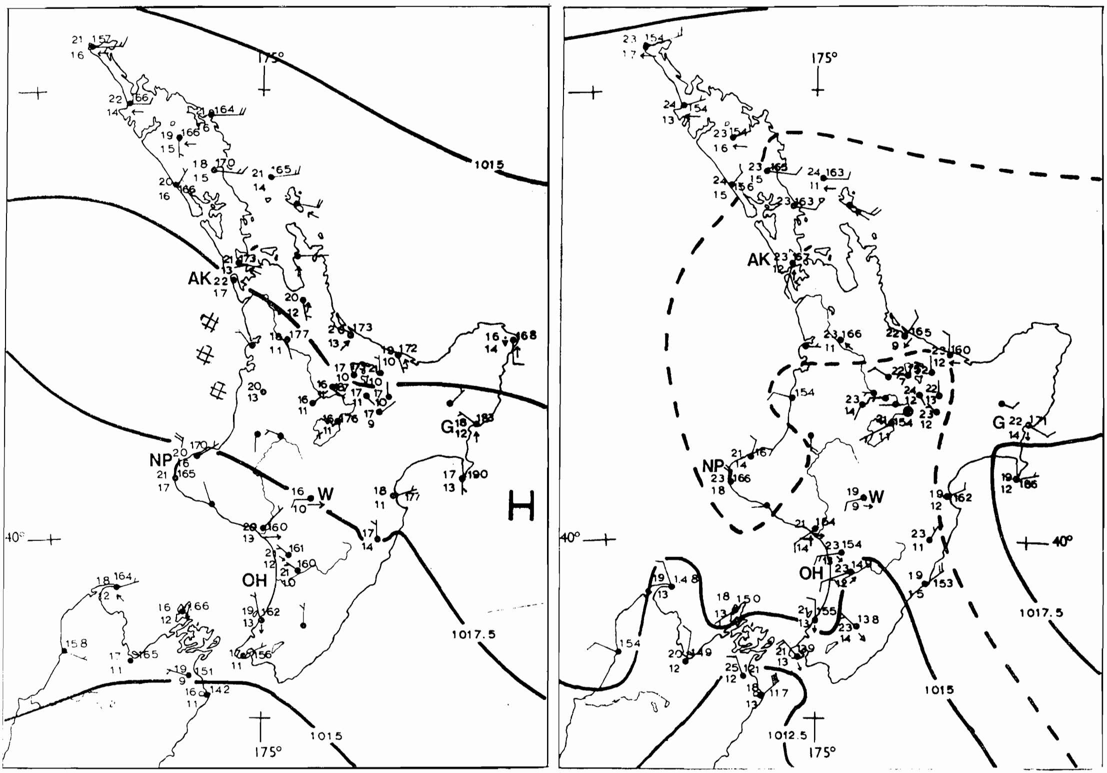
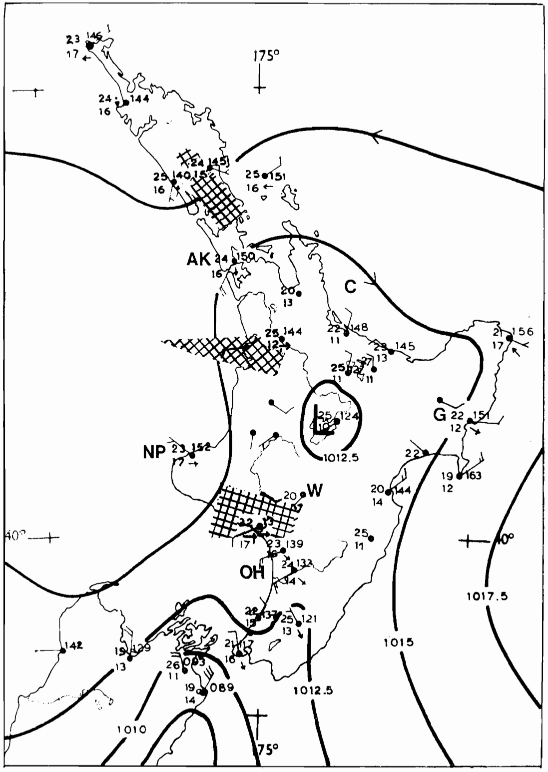


FIG. 3—Surface weather data and mean sea level pressure analysis for North Island on 18 January 1974; Fig. 3a (above left) at 0900; Fig. 3b (above right) at 1200; and Fig. 3c (right) at 1500 NZST. The location of each reporting station is shown by a heavy black dot. Temperature and dew point (°C) is shown on the left of each station. Pressures (reduced to sea level) in tenths of a millibar (with the initial two digits omitted) are shown on the right. Wind direction is plotted as an arrow, with the arrow head terminating at a point on the windward side of the station dot. Wind speed is indicated by barbs and half barbs on the arrow shaft. Each whole barb represents 10 knots and each half barb 5 knots. Speeds of less than 3 knots are indicated by an absence of barbs on the direction line and in the case of "calms" the line is replaced by a circle round the station dot. Low cloud movements are shown by arrows below the dot. Isobars at 2.5 mb intervals are shown by solid lines; some intermediate isobars are dashed. AK, Auckland; G, Gisborne; NP, New Plymouth; OH, Ohakea: W, Waiouru.



At 0900 a narrow ridge of high pressure extended over the central North Island. Winds north of Taupo were generally from the easterly quarter. Although the weather was mainly fine some precipitating clouds were detected by radar off the west coast.

By midday pressures had fallen; the largest fall over the three-hour period ending at midday was 2.2 mb at Taupo. Onshore winds (sea breezes) had developed in many coastal places. Although winds in the Bay of Plenty area were predominantly northerlies, there were westerlies reported by Forest Products and Forest Service stations in the area north of Taupo. (However at the time of lighting of the fire the local wind was east of north.)

By 1500 there was a closed 1012.5 mb isobar over the Taupo area. There were sea breezes about the coast. The winds indicated the tendency for a circulation to develop around the low pressure area. Convective cloud build-ups were reported in many areas. Strong rain echoes were detected by the Auckland weather radar in the Raglan-Hamilton area.

The pressure pattern shown on the 1500 map is known as a *heat low*. These patterns develop over New Zealand on summer afternoons when the pressure gradient due to the large scale flow is weak. Intense solar radiation during the day and the different thermal properties of land and ocean cause surface temperatures on the land to be greater than those at sea. A seawards flow is induced at higher levels with pressures at the surface becoming less than those over the sea. A compensating onshore flow—the sea breeze—develops at low levels. Frictional retardation of the low level flow helps to maintain the pressure deficit over the land. The Coriolis force (effect of the Earth's rotation) gradually tends to make the air flow around the low pressure area rather than directly towards the low pressure centre.

The rising of the air in the vicinity of a well-organized heat low such as that of 18 January 1974 makes the lapse rate (temperature decrease with height) become large. Conditions of neutral stability or even instability are attained i.e. conditions such that a parcel of air given some slight additional heating can rise to a great height.

Thus the presence of a well-defined heat low is an indication of the likelihood of low stability—though it is not the only situation in which low stability may occur.

Stability

Data on atmospheric temperature, pressure and humidity above ground level are obtained by radiosonde (sensors attached to a radio transmitter borne aloft by balloon). The nearest radiosonde station to Pouakani is at Waiouru about 130 km to the south. Radiosondes are released daily at 1100. Although Waiouru is at a much higher elevation than Pouakani the soundings made there should give a quite good representation of ambient conditions in the vicinity of the fire.

A useful measure of atmospheric stability is an index derived as follows. A parcel of air is assumed to rise dry adiabatically (i.e. without mixing with its environment and without any other heat exchange) until it becomes saturated. It is then assumed to continue to rise — again without mixing or other heat exchange — but will no longer cool so rapidly since latent heat is released. (This process is loosely referred to as saturated adiabatic ascent.) On reaching a pressure of 500 mb (about 5800 m) the parcel's temperature is compared with that of the environment. If the lifted parcel emerges warmer than its surroundings (positive index) the atmosphere is unstable; if it emerges cooler than its environment (negative index) the atmosphere is stable.

Of course real air parcels never rise without some exchange of heat and mass with their environment. The stability index is therefore only a guide as to the intensity of any convection. Its advantage over some other stability parameters is that it accounts for both unsaturated (clear air) and saturated (cloud) ascent.

On 18 January 1974 the index had a value of +1. The index was also computed for all other days in January and February 1974. On six other days the index was positive; the largest value was +3. However some of these days were quite moist — in some cases there was actually rain in the area.

Another parameter useful for determining the stability of the lower atmosphere is the mean lapse rate between the surface and 700 mb (about 3000 m). On 18 January the mean lapse rate of this layer was 9.2°C/km, only slightly less than the dry adiabatic rate of 9.77°C/km. A survey of all summer (December-January-February) data for Waiouru for the period December 1966 to December 1973 revealed that mean lapse rates in this layer greater than 9°C/km occur on 3.2% of days and mean lapse rates exceeding 10°C/km occur on 0.5% of days.

These two parameters indicate that the stability was low on 18 January 1974 but not exceptionally so.

Upper Winds

Data on winds above the surface are obtained by tracking a balloon-borne target by radar or by following a balloon with a theodolite. The latter method is possible only until the balloon enters cloud or for other reasons can no longer be seen by the theodolite operator.

The nearest places to Pouakani at which radar data are obtained are Auckland and Ohakea. Theodolite data from Gisborne, Rotorua and New Plymouth can be used in wind analysis at lower levels. The wind data were obtained at 1100 and 1700.

From the available data the following wind profile is estimated for the Pouakani area at the time of the whirlwind.

At the level of the ridge tops the wind was west to southwest and about 10 knots*. At levels between the ridge tops and 3000 m the wind speed was probably similar or slightly less with the direction turning gradually more southerly with height. Over the range 3000-6000 m the wind was probably about 5 knots and of variable direction. Above this level the winds were again southwesterly with the speed gradually increasing up to about 11 000 m where the speed was probably 40 to 50 knots.

Because upper wind data are not obtained from Waiouru no statistics on the two-way frequency distribution of wind and stability are available for the central North Island. It seems probable that the combination of a deep layer of winds of about 10 knots or less and low stability as occurred on 18 January is rather infrequent.

There does not seem to have been a region of pronounced wind speed decrease with height such as Byram (1959) has linked with blow up fires.

There is some evidence that the convection column extended into the region of strong southwesterly winds at high levels. All hourly observations made at Whakatane,

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* This non-S.I. unit still important; very closely, 1 knot = 0.5 m/s.

some 120 km to the northeast, on the afternoon of 18 January included remarks about an extensive layer of smoke. As far as is known there were then no other major fires in the central North Island-Bay of Plenty area other than the one at Pouakani. Another indication that the convective column extended to high levels was the development of a very heavy shower (encountered by officers of New Zealand Forest Products Ltd approaching Pouakani by road immediately after the whirlwind). Although there were other showers in some other central North Island areas that day it seems likely that the one near Pouakani was produced by a cumuliform cloud initiated by the fire's convective column.

DISCUSSION AND CONCLUSIONS

The large whirlwind at Pouakani occurred in a situation with low stability and relatively light winds in a deep layer associated with a heat low.

The source of the swirling motion could have been either

(i) The circulation about the heat low itself, or

(ii) a concentration of vorticity in the northwestern sector of the heat low near the boundary of the west to southwest and north to northeast surface wind flows. Surface convergence and hence vertical motion might also have been enhanced in this region.

(iii) The third possible source of the vorticity is swirling in the lee of hills. The rather low-velocity surface and near-surface winds and the relatively slight slopes in the area do not favour this possibility. I consider (ii) as the most probable source.

The whirlwind moved in a generally northeast direction but there were some small changes in direction. The path of the whirlwind was generally downhill. The motion can be explained in two different ways.

One possibility is that the whirlwind developed on a lee slope and moved downslope steered by the west to southwest wind at or immediately above the ridge top level.

Alternatively the whirlwind formed almost in situ in the fairly light winds below 6000 m. Once the convective column penetrated the zone of strong southwest winds above 6000 m, exchange of momentum between high and low levels steered the whirlwind to the northeast.

A remarkable feature of this whirlwind was the unburnt strip associated with it. Since the whirlwind was moving it is apparent that the part of the system that was not burning could not have been in the core of the whirlwind. Possibly the intensity of the fire was so great that the air swirling on one side of the whirlwind core was so depleted in oxygen that no burning could occur.

Some of the conclusions reached in this paper are necessarily tentative. Inadequate data for the immediate vicinity of the fire — both at the surface and at higher levels — makes it impossible to be more definite.

There is a long way to go before meteorologists or foresters can confidently predict the evolution of every fire. However recognising certain weather patterns such as heat lows that are likely to be associated with deep layers of unstable air and knowledge of the causes of local wind variations can probably be of assistance in assessing fire development. To be most effective the meteorologist concerned must have a sound knowledge of local topography.

When large burns are attempted or wild fires get out of control the meteorologist can be of greatest assistance in predicting the evolution of the fire if special observations are made in the vicinity.

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Appendix — Formation of whirlwinds

In conditions of instability a deep convective circulation can occur over a fire with air being drawn in at low levels rising in a column, spreading out at higher levels and then descending. If the air drawn into the fire is not initially at rest but has some slight rotational motion about a vertical axis (for simplicity, assumed to coincide with the centre of the fire), the air parcels ascend in a spiral fashion, the radius of the spiral decreasing and the rotation rate increasing in the lower levels but the radius increasing and the rotation rate decreasing at higher levels.

In the constricted part of the spiral pressure is less than at higher or lower levels. One might expect air to rush in from below or above to make up this pressure deficit. However, if the constricted area is close to the ground any inflow from below is impeded; thus fire vortices have their bases quite low. The upper part of the constricted area is in the region of strong buoyancy where vigorous upward motion prevents any backflow.

The vertical **vorticity** is a measure of the spin of the horizontal component of the wind about a vertical axis. In mathematical terms it is $\nabla \times V$ where V is the wind velocity. For a rotating solid body the vorticity is twice the angular velocity. The vorticity of a small fire "devil" is estimated at about 1 s^{-1}. Larger fire whirlwinds have vorticities of the order of $1 \times 10^{-1} \text{ s}^{-1}$:

The dominant feature in the production of fire whirlwinds is the constriction of existing rotational flows by convection with a consequent increase in vorticity. What are the sources of this vorticity?

(1) Typical mid-latitude depressions or anticyclones as seen on a weather map have a vorticity of about 10^{-5} s^{-1}. If these features were the source of the vorticity of fire whirlwinds

the convection would have to increase the vorticity by at least four orders of magnitude.

(ii) Smaller scale meteorological phenomena may be a source of rather greater local vorticity. These include such features as squall lines, depressions due to differential heating during the day and regions where there are marked horizontal variations of wind speed, i.e. zones of horizontal wind shear. Barcilon and Drazin (1972) have demonstrated that in a horizontal shear flow under unstable conditions a strong vortex with a vertical axis is generated. Their work based on an interest in dust devils is also relevant to fire-induced vortices.

(iii) In hilly country or in built-up areas swirls develop in valleys and around buildings. The fire whirlwinds on lee slopes reported by Graham (1952, 1955) presumably originated from such swirls.

(iv) Even over flat terrain vorticities with axes of rotation in all directions are created by turbulence in windy conditions. Those with vertical axes could be a source of vorticity for some fire whirlwinds.