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# SOME METEOROLOGICAL ASPECTS OF THREE INTENSE FOREST FIRES

By R. J. TAYLOR,* D. G. CORKE,† N. K. KING,‡ D. A. MACARTHUR,‡
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*Abstract*

We report a study of three intense forest fires, all of area about 30 $\mathrm{km}^2$, in which convection extended to heights ranging from 2750 m to 4300 m. The observations taken comprise surface-level wind, temperature, and humidity; mean temperature, temperature fluctuations, and vertical acceleration as measured from an aircraft; the rate of change of height of the aircraft while it was held at constant attitude; and wind profiles from double-theodolite pilot-balloon flights.

Strong inflow into the smoke columns from all directions was observed to heights of at least 300 m. The consequent strong updrafts were manifest in large and rapid changes of the aircraft's height while penetrating the smoke directly above the fire at heights up to about 1 km, where there was intense turbulent activity. At greater heights, and away from the central area of the fire, the turbulence characteristics of the heated air were little different from those of the ambient unheated air.

From heat conservation principles, a mean entrainment rate of 1.037 (standard error 0.002) per 100 m is deduced. Using this entrainment rate a particularly simple method of predicting the height of convection is proposed for situations where the atmosphere is not conditionally unstable; condensation levels derived from simple surface measurements may be used in this calculation. When conditional instability is present, standard meteorological methods of allowing for entrainment must be employed to obtain a satisfactory estimate of the height of convection.

In the hottest fire the latent heat evolved from condensation was almost as great as that produced from the burning fuel on the ground.

## I. INTRODUCTION

The meteorological processes associated with the development of wild-fires are difficult to study in any but a general way, yet they are of special interest to research workers concerned with bushfire behaviour.

It is usually pointless to set up instruments in the path of a major wild-fire, for changes in fire behaviour can be so rapid that there is little chance of obtaining significant observations; furthermore in many instances observers close by are rather more concerned with survival than with making measurements. In December 1969 the Western Australian Forests Department arranged a series of three intense burns in an attempt to simulate wild-fires for detailed study. These were purposely lit in an uninhabited forest area and measurements were made from a number of observation points nearby, and from an aircraft which flew near and through the smoke columns produced.

The countryside in which the fires were lit was fairly flat, with occasional gentle undulations; fuel quantities (forest litter and combustible scrub) ranged from 2½ tons

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per acre in scrub to 7½ tons per acre, or more, in poor quality jarrah (*Eucalyptus marginata*). Each block was greater than 10,000 acres in area but a protective break had been burned around each of them to prevent the fires from spreading; although this reduced the effective sizes of the blocks the residual areas which still contained fuel were between 7 and 7½ thousand acres for all three fires. Since the calorific value of the fuel can be taken as about 4500 cal $g^{-1}$* in these particular experiments (cf. Pompe and Vines 1966), 1 ton per acre of fuel burnt corresponds to a heat output of about 112 cal $cm^{-2}$.

As a further precaution, to prevent the unwanted spread of fire, a large section of the surrounding countryside had been previously control-burned from an aircraft using the technique described by Baxter, Packham, and Peet (1966) and Packham and Peet (1967). The same technique was used to light up the experimental blocks; on each occasion the area involved was ignited more or less uniformly with numerous spot fires scattered all over it. Lighting up took between 1½ and 2 hr, and each fire was at its peak shortly afterwards, between 1200 and 1300 hr in all three cases. Combustion was so rapid that within a further hour the fuels were virtually exhausted.

## II. OBSERVATIONS

### (*a*) *General*

The locations of the fires and surrounding observation points are indicated in Figures 1–4; these figures also give a geographical reference point and show where

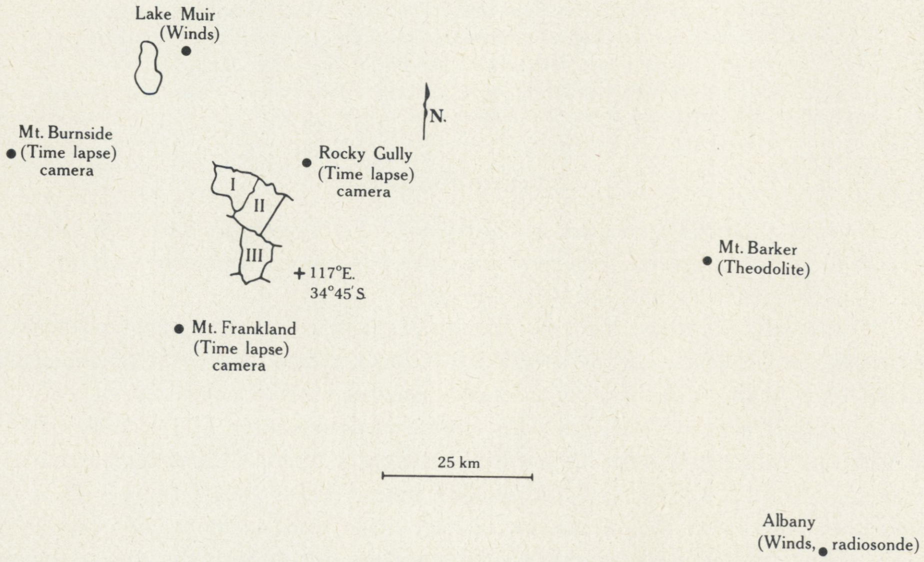

Fig. 1.–Map showing positions of fire areas and observation sites.

the various airborne measurements, as described below, were made. A theodolite and camera were set up at Mount Barker, about 80 km (50 miles) east of the fire area, in

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* In these experiments all the fires were much more intense than in a similar investigation reported previously (Taylor *et al.* 1968), and because combustion of forest litter was more complete the heat of combustion of the fuel has been increased from 4000 to 4500 cal $g^{-1}$.

order to determine condensation levels and the heights of the convection columns. There were also simple meteorological stations on the ground in the vicinity of each fire. Time-lapse motion picture cameras were situated at various vantage points to photograph the smoke columns, and provide detailed records of fire behaviour. Upper wind measurements, using pilot balloons, were made from flat terrain some distance to the north-west.

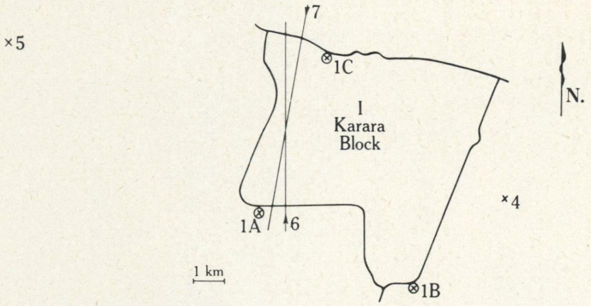

Fig. 2.—Detailed site map showing positions of ground stations ⊗, temperature soundings X, and traverses (arrows), for Karara block.

The proportions of leaf litter and scrub in each of the fire areas had been assessed in some detail by officers of the Forests Department. The first block to be burned – "Karara" in Figure 2 – contained the least scrub, and the last – "Surprise" in Figure 4 – had the most; fuel quantities were therefore heaviest for the first fire.

Fig. 3

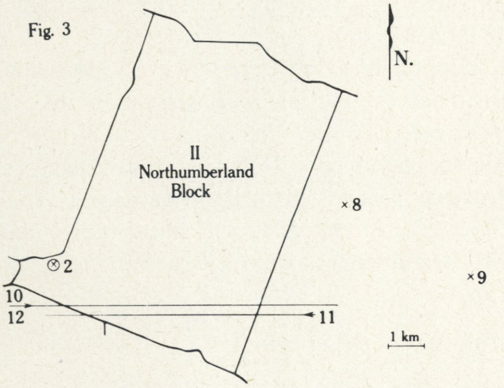

Fig. 4

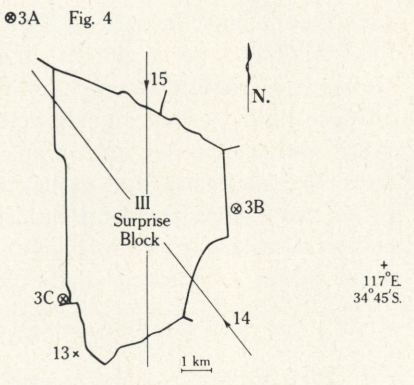

Fig. 3.—Detailed site map, Northumberland block. Symbols as for Fig. 2.

Fig. 4.—Detailed site map, Surprise block. Symbols as for Fig. 2.

However, the rate of spread of fire in the scrubby areas was more than twice that in leaf litter, and allowance for this had to be made in determining burning rates which were calculated for each fire from the fuel assessment maps. Table 1 shows the area, fuel quantity, and maximum burning rate for each fire.

### (*b*) *Aircraft Measurements*

A twin-engined Cessna 337 Super Skymaster was used to carry the airborne equipment, which was the same as that described in an earlier investigation (Taylor *et al.* 1968). It comprised electrical resistance thermometers – for measuring both mean temperatures and rapid temperature fluctuations – and an accelerometer, the outputs of all three instruments being recorded on an SFIM photographic recorder. Unfortunately the mean temperature recorder developed a circuit fault which caused it to drift – and on only four occasions could the rate of drift be estimated, and allowed for sufficiently accurately, for temperature changes to be followed over periods of a few minutes. As a consequence, vertical temperature profiles were measured with the aircraft thermometer, reading from a dial in the cabin. The time constant of this instrument was estimated to be about 10 sec,* and since all profile measurements were made by holding the aircraft at each altitude for 30 sec, there was adequate time for the thermometer to reach equilibrium. The readings of the aircraft thermometer also agreed, to better than 1°C, with those of a specially calibrated alcohol-in-glass thermometer inserted in the cabin air intake.

TABLE 1

GENERAL INFORMATION ON FIRES

| Block | Date of Fire | Area Burned |  | Fuel Quantity (ton/ac) | Est. Max. Burning Rate (ton $ac^{-1}$ $hr^{-1}$) | Max. Rate of Heat Output (cal $cm^{-2}$ $min^{-1}$) |
|---|---|---|---|---|---|---|
|  |  | (ac) | ($km^2$) |  |  |  |
| Karara | 5.xii.69 | 7500 | 30 | 6.0 | 3.9 | 7.3 |
| Northumberland | 6.xii.69 | 7500 | 30 | 5.3 | 4.1 | 7.7 |
| Surprise | 13.xii.69 | 7000 | 28 | 5.0 | 2.9 | 5.4 |

Another type of aircraft observation, referred to as a "traverse", was also made. During each traverse the aircraft was held at constant attitude with respect to the artificial horizon while the altimeter was read every 10 sec. In this way, some information is obtained about vertical air velocity components on a scale sufficiently large to move the whole aircraft – though it is, of course, recognized that the vertical motions of air and aircraft are not identical. The locations of the vertical temperature soundings and traverses are shown in Figures 2–4. All measurements from the aircraft were made at an indicated air speed of 85 knots (44 m $sec^{-1}$).

### (*c*) *Ground Based Meteorological Observations*

Pilot balloon ascents, by use of two theodolites on a baseline of 600 m, were made at frequent intervals from an open, level site at Lake Muir about 30 km (*c.* 20 miles) to the north-west of the fires. It was thought advisable not to work any closer to the fires than this, as smoke was expected to rise to considerable heights and its drift could not be accurately predicted. For the fire of December 6, 1969 winds could not be measured above 2500 m because of their strength, and the observations have been supplemented by radar winds as determined by the Commonwealth Bureau of Meteorology, at Albany, about 100 km (60 miles) south-east of the fire area (flight commencing 1315 hr local time). As there was reasonable agreement between the

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*This estimate was obtained on an occasion when the lapse rate in the atmosphere seemed to be nearly constant with height from 2500 to 5000 ft; the time constant was determined by comparing temperature readings taken during a fairly slow ascent (400 ft/min) with corresponding readings made immediately afterwards on a rapid descent (2140 ft/min) through this layer.

measurements at lower levels, this extrapolation is probably satisfactory; furthermore, on the days of the other two fires, radar winds at all levels compared well with those obtained during the pilot balloon flights. The mean winds over the life-time of each fire are shown in Figure 5.

No attempt was made to measure the horizontal convergence by an array of pilot balloon stations; recent calculations and observations by Clarke *et al.* (1971) have shown that to do this with acceptable accuracy requires an elaboration of instrumentation and communications which would have been quite impossible in the forest areas concerned, unless the stations had been situated so close to the fires that obscuration of the balloons by trees and smoke would have been almost inevitable.

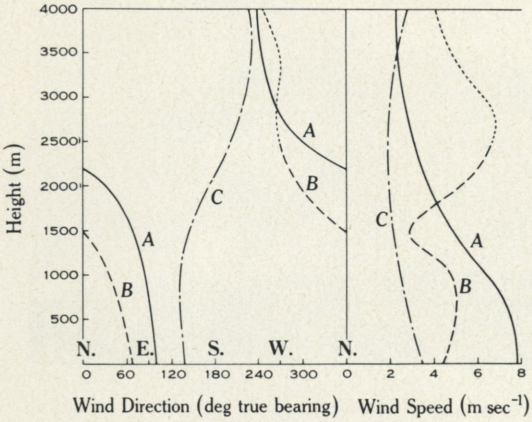

Fig. 5.–Upper winds.
*A*, Dec. 5, 1969;
*B*, Dec. 6, 1969;
*C*, Dec. 13, 1969.
The dotted extension of the curves for December 6, 1969 above 2500 m show radar winds at Albany (flight commencing 1315 hr local time).

It was intended to have three ground stations, each comprising a recording thermohygrograph and recording anemometer adjacent to each site. However, the occurrence of suitable conditions for burning on two successive days made it impossible to move the ground stations between the fires on Karara block (December 5, 1969) and Northumberland block (December 6, 1969), so that there is only one station adjacent to the latter fire. The thermohygrographs gave weekly records; temperatures and humidities were checked against an Assmann psychrometer as the charts were put on and taken off, and on one other occasion during each week. A maximum thermometer in the screen with each thermohygrograph gave a further check. The anemometers were of the Lambrecht (Woelfle)-type and gave a record of direction as well as speed. The positions of the ground stations are given in Figure 2, 1A, 1B, 1C denoting the Karara block; in Figure 3, 2 denoting the Northumberland block; in Figure 4, 3A, 3B, 3C denoting the Surprise block.

### (*d*) *The Appearance of the Smoke Columns*

For all three fires the winds were generally easterly at the lower levels and westerly above (see Fig. 5). However, although most of the smoke appeared to follow the measured winds at the appropriate levels, considerable amounts of smoke also moved north and south for some 4–6 km (3–4 miles), giving a distinct "mushroom" shape to the column – a typical photograph is shown in Figure 6. This was possibly due to circulation induced by the strong baroclinicity close to the fire edge (see Section 3(*d*) below).* Other views of the smoke columns are given in Figures 7 and 8.

Fig. 6.–"Northumberland" fire of December 6, 1969 photographed from the observation point near Rocky Gully. The distinct mushroom shape of the smoke column may be clearly seen below the condensation clouds over the fire area.

It was, in fact, possible to fly the aircraft right around the smoke column of each fire, below a thick layer of smoke at a height of about 1–1½ km, and though

Fig. 7.–Aerial photograph of the upwind edge of "Karara" fire (December 5, 1969).

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*On the other hand, the mushroom may be associated with condensation clouds formed above the fires which the time-lapse pictures recorded on many occasions. Analysis showed that the tops rose at 3–3½ m $\mathrm{sec}^{-1}$; they then fell backwards again at about the same velocity, presumably because they overshot their equilibrium positions.

the smoke level was lowest "downwind" with respect to the low-level winds, there was still a corridor of clear air up to a height of 300 m or more. This latter observation is in accord with our previous experiences of milder controlled fires (Taylor *et al.* 1968) when, at the downwind edges, similar corridors of clear air extended up to about 250 m. It was also in accord with the general reports of suppression crews working close to the present more intense fires, who consistently noticed that winds near the ground blew *into* the fires everywhere along their perimeters.

Fig. 8.—"Surprise" fire of December 13, 1969; photograph taken as the aircraft started a traverse through the centre of the smoke column. The corridor of clear air at the downwind edge of the fire is clearly visible on the right-hand side of the picture.

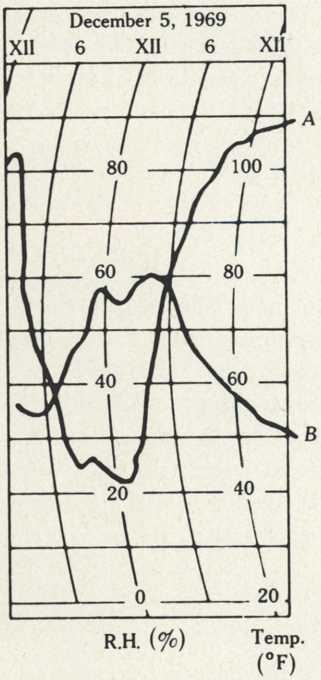

Fig. 9.—Thermohygrograph traces showing obscuration of the sun at station 1B (Karara block) on December 5, 1969; the fire was at its peak at *c.* 1300 hr. Time as shown by the temperature trace is correct; the relative humidity trace shows time 3 hr slow due to the necessary offset of the pens. *A*, R.H. trace; *B*, temperature trace.

The formation of the mushroom shaped smoke clouds mentioned above was detected by the ground stations nearby. Since the last two fires were at their peak close to noon and the first at about 1300 hr, the sun was near its maximum altitude on each occasion; and, as the smoke moved out above the stations and slowly obscured the sun, this became evident on the temperature and relative humidity records. A typical example is shown in Figure 9.

## III. RESULTS

The considerable height to which the smoke rose and the variation of wind direction with height combined to spread smoke over a wide area. As a result, navigation of the aircraft by visual reference to landmarks in the vicinity of the fires was considerably more difficult than in the work reported previously (Taylor *et al.* 1968). It might be expected, too, that the intense convective activity could produce turbulent motion in the smoke column which might constitute a danger to aircraft. Consequently flight through the centre of the smoke column was approached with some caution and only after exploring more distant regions. As a result, the core of the smoke column (the "stem" of the "mushroom") was penetrated only twice (on December 13, 1969) while the fire was close to its maximum intensity. In what follows, these two traverses will be singled out for special mention.

### (*a*) *SFIM Records*

These were digitized at intervals of 1/32 in., the chart speed being a nominal 1 in. per sec. Standard deviations of acceleration and temperature ($\sigma_a$ and $\sigma_T$ respectively), and the coefficients of correlation, $R_{aT}$, between them, were evaluated on a digital computer. The results are given in Table 2. Due to engine vibration, the accelerometer trace often showed an undesirable degree of broadening and for this reason $\sigma_a$ values are given only to the nearest 0.1 m $\text{sec}^{-2}$. The temperature fluctuation trace was, however, quite clear, and $\sigma_T$ values are probably correct to about 0.02°C. Maximum accelerations observed were about ±10 m $\text{sec}^{-2}$ (±1 g).

### (*b*) *Traverses*

The aircraft traverses were carried out by flying towards the smoke column from one side in clear air, then through the column and continuing in the clear air on the other side, in order that the motions of heated and unheated air might be compared. The mean vertical velocities $\bar{w}$ and their standard deviations $\sigma_w$ are given in Table 3. The mean excesses of $\bar{w}$ and $\sigma_w$ in the smoke columns over those outside them are respectively $1.9 \pm 0.7$* m $\text{sec}^{-1}$ and $1.4 \pm 1.0$* m $\text{sec}^{-1}$. The highest upward vertical velocity encountered in the smoke (on the second traverse of December 13, 1969) was 15 m $\text{sec}^{-1}$ (*c.* 3000 ft/min) as an average over 10 sec, or 13 m $\text{sec}^{-1}$ as averaged over a 30 sec interval. Significant downdrafts were also encountered on occasions in clear air close to the smoke column.

### (*c*) *Vertical Temperature Soundings*

Air temperatures in the clear air were read after holding the aircraft at each altitude for 30 sec, in order to allow the thermometer to come to equilibrium. The

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*This notation will be used to denote the standard error of the mean.

## TABLE 2

## TURBULENT FLUCTUATIONS

| Date 1969 | Time | Height (m) | Location (Figs. 2–4) | Clear Air or Smoke | $\sigma_a$ (m $sec^{-2}$) | $\sigma_T$ (°C) | $R_{aT}$ |
|---|---|---|---|---|---|---|---|
| Dec. 5 | 1158 | 460 | 4 | clear | 1.1 | 0.15 | 0.13 |
| | 1200 | 610 | 4 | clear | 0.8 | 0.12 | 0.25 |
| | 1205 | 920 | 4 | clear | 1.4 | 0.23 | 0.42 |
| | 1211 | 1220 | 4 | clear | 0.8 | 0.05 | –0.04 |
| | 1222 | 1830 | 4 | clear | 0.3 | 0.02 | 0.01 |
| | 1235 | 2440 | 4 | clear | 0.7 | 0.10 | 0.30 |
| | 1241 | 3050 | 4 | clear | 0.6 | 0.04 | 0.36 |
| Dec. 5 | 1300 | 3050 | 5 | smoke | 0.4 | 0.01 | 0.49 |
| | 1305 | 2440 | 5 | smoke | 0.7 | 0.08 | 0.19 |
| | 1307 | 2140 | 5 | smoke | 0.5 | 0.12 | 0.23 |
| | 1310 | 1830 | 5 | smoke | 0.6 | 0.19 | 0.08 |
| | 1314 | 1520 | 5 | smoke | 0.7 | 0.13 | 0.75 |
| | 1318 | 1220 | 5 | smoke | 0.6 | 0.23 | 0.32 |
| | 1320 | 920 | 5 | smoke | 0.7 | 0.16 | 0.22 |
| Dec. 5 | 1336 | 2140 | 6 | clear | 0.6 | 0.35 | 0.26 |
| | 1338 | 2140 | 6 | smoke | 0.6 | 0.25 | –0.17 |
| | 1350 | 1220 | 7 | clear | 0.8 | 0.07 | 0.58 |
| | 1353 | 1220 | 7 | smoke | 0.8 | 0.19 | 0.26 |
| Dec. 6 | 1140 | 460 | 8 | clear | 1.4 | 0.24 | 0.37 |
| | 1143 | 610 | 8 | clear | 0.9 | 0.08 | –0.06 |
| | 1146 | 920 | 8 | clear | 0.8 | 0.12 | 0.20 |
| | 1150 | 1220 | 8 | clear | 0.7 | 0.13 | 0.25 |
| | 1152 | 1520 | 8 | clear | 0.8 | 0.60 | –0.27 |
| | 1155 | 1830 | 8 | clear | 0.5 | 0.11 | –0.67 |
| | 1200 | 2440 | 8 | clear | 0.5 | 0.12 | –0.08 |
| | 1206 | 3050 | 8 | clear | 0.3 | 0.02 | 0.53 |
| Dec. 6 | 1225 | 3050 | 9 | smoke | 0.8 | 0.07 | 0.85 |
| | 1236 | 1980 | 9 | smoke | 0.6 | 0.09 | 0.00 |
| | 1238 | 1830 | 9 | smoke | 0.4 | 0.06 | –0.29 |
| | 1254 | 1680 | 10 | smoke | 0.7 | 0.18 | –0.07 |
| | 1313 | 920 | 12 | smoke | 0.5 | 0.12 | 0.06 |
| Dec. 13 | 1215 | 460 | 13 | clear | 1.3 | 0.18 | 0.41 |
| | 1217 | 610 | 13 | clear | 1.2 | 0.17 | 0.48 |
| | 1220 | 920 | 13 | clear | 0.7 | 0.10 | –0.13 |
| | 1223 | 1220 | 13 | clear | 0.8 | 0.18 | 0.41 |
| | 1228 | 1830 | 13 | clear | 0.5 | 0.10 | 0.36 |
| | 1234 | 2440 | 13 | clear | 0.5 | | |
| | 1240 | 3050 | 13 | clear | 0.4 | 0.08 | 0.37 |
| Dec. 13 | 1311 | 990 | 14 | clear | 0.7 | 0.41 | –0.08 |
| | 1313 | 1010 | 14 | smoke | 1.6 | 0.66 | 0.08 |
| | 1321 | 1060 | 15 | clear | 0.7 | 0.15 | 0.39 |
| | 1323 | 1290 | 15 | smoke | 2.3 | 1.55 | 0.44 |
| *Averages* | | | | | | | |
| Clear air | | 1480 | | | 0.1 | 0.16 | 0.19 |
| Smoke (all) | | 1760 | | | 0.1 | 0.26 | 0.22 |
| Smoke (exc. 13th) | | 1850 | | | 0.1 | 0.14 | 0.21 |
| Smoke (13th only) | | 1150 | | | 2.0 | 1.10 | 0.26 |

resulting profiles are shown by the lines *AB* in Figures 10–12. In the case of Figure 11, which represents the fire of December 6, 1969, the highest level where the temperature was read was 3360 m. The point plotted as –2°C at 4300 m is based on an extrapolation of the general trend of the uppermost five observations, and is in reasonable agreement with the value of –3°C, as measured at this level during the Albany radiosonde flight – at 0715 hr local time that day. In view of what is said below about the height attained by this fire, it must be emphasized that there is no evidence that this height was limited by a pre-existing inversion or strongly stable layer.

TABLE 3

VERTICAL VELOCITIES FROM TRAVERSES

| Date 1969 | Time* | Height* (m) | Location (Figs. 2–4) | Clear Air or Smoke | $\overline{w}$ (m sec$^{-1}$) | $\sigma_w$ (m sec$^{-1}$) |
|---|---|---|---|---|---|---|
| Dec. 5 | 1336 | 2140 | 6 | clear | –0.7 | 1.0 |
| | | | 6 | smoke | –0.6 | 0.8 |
| Dec. 5 | 1350 | 1220 | 7 | clear | –0.5 | 1.5 |
| | | | 7 | smoke | +0.1 | 0.2 |
| Dec. 6 | 1253 | 1680 | 10 | clear | –0.2 | 0.2 |
| | | | 10 | smoke | –0.1 | 0.8 |
| Dec. 6 | 1304 | 1220 | 11 | clear | –0.7 | 0.9 |
| | | | 11 | smoke | +1.8 | 1.3 |
| Dec. 6 | 1312 | 920 | 12 | clear | –0.5 | 2.0 |
| | | | 12 | smoke | +1.0 | 3.1 |
| Dec. 13 | 1311 | 1040 | 14 | clear | –0.3 | 0.8 |
| | | | 14 | smoke | +4.1 | 3.9 |
| Dec. 13 | 1321 | 1060 | 15 | clear | 0.0 | 0.3 |
| | | | 15 | smoke | +4.2 | 6.7 |
| *Averages* | | | | | | |
| Clear air | | | | | –0.4 | 1.0 |
| Smoke (all) | | | | | +1.5 | 2.4 |
| Smoke (excluding 13th) | | | | | +0.4 | 1.2 |
| Smoke (13th only, mean of two) | | | | | +4.2 | 5.3 |

* At beginning of run.

### (*d*) *Horizontal Temperature Gradients*

The degree of baroclinicity of the atmosphere, one of the main factors controlling the rate of conversion of thermal energy into kinetic, is given by the vector product of the gradients of pressure and specific volume. In situations where the horizontal temperature gradient is large, this becomes the dominant term in the vector product, and one might thus expect some degree of correlation between horizontal temperature gradient and the intensity of convective activity as indicated by $\sigma_w$. As noted previously, the mean temperature recorder was not stable; however, there were four occasions, in parts of traverses close to the edge of the smoke, when one could estimate and correct for the rate of drift with a reasonable degree of confidence and so arrive at an estimate of horizontal temperature gradient. On the basis of work already reported (Taylor *et al.* 1968) allowance for change in height of the aircraft was made at the dry adiabatic rate, since all four sets of observations were made below condensation level. The values of horizontal temperature gradient ($\partial T/\partial x$) and $\sigma_w$ are given in Table 4. The largest values of both $\partial T/\partial x$ and $\sigma_w$ were obtained on the two traverses of December 13 when the central region of the fire was penetrated.

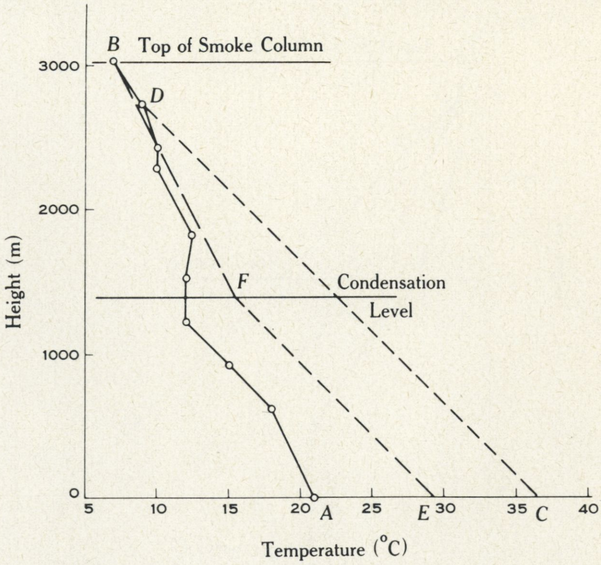

Fig. 10.–Temperature structure, December 5, 1969. —— environmental lapse rate; ----- dry adiabatic lapse rate; — — — saturated adiabatic lapse rate.

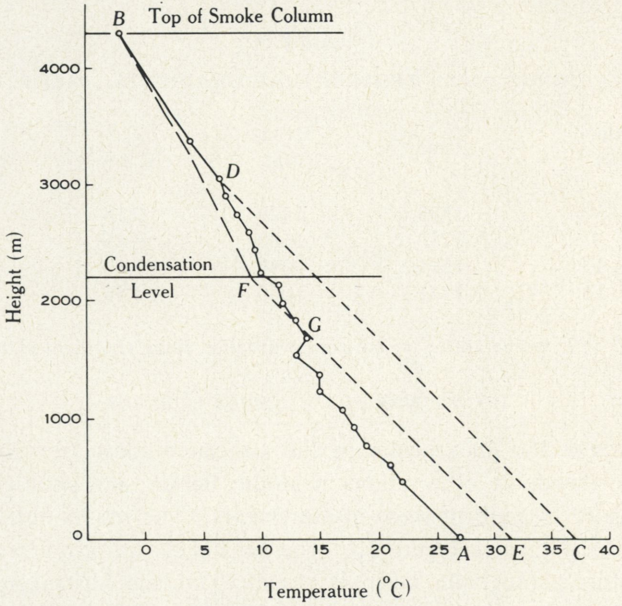

Fig. 11.–Temperature structure December 6, 1969. Lines as in Fig. 10. (The point *B* is estimated as in text.)

For comparison, there are available horizontal temperature gradients from flights through sea-breeze fronts together with altimeter readings every 6 sec (unpublished work carried out under the direction of R. H. Clarke); during these measurements the aircraft was, once again, held at constant attitude. The sea-breeze values of $\partial T/\partial x$ and of $\sigma_w$ are given in Table 5.

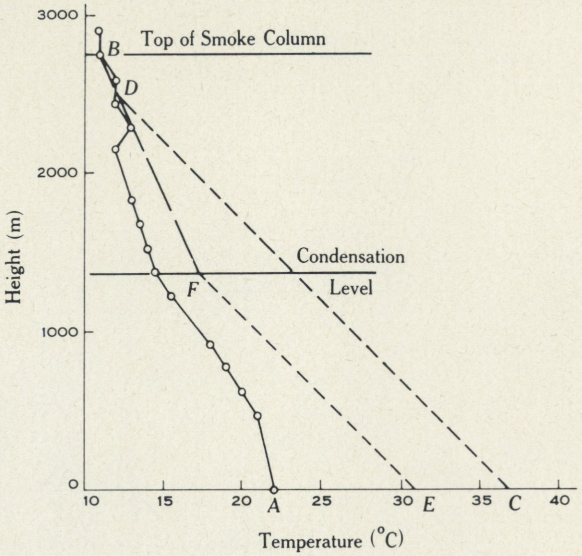

Fig. 12.–Temperature structure December 13, 1969. Lines as in Fig. 10.

TABLE 4

HORIZONTAL TEMPERATURE GRADIENTS: FIRES

| Date 1969 | Time | Height (m) | $\partial T/\partial x$* (°C km$^{-1}$) | $\sigma_w$ (m sec$^{-1}$) |
|---|---|---|---|---|
| Dec. 5 | 1350 | 1220 | 0.18 | 0.2 |
| Dec. 6 | 1253 | 1680 | 0.15 | 0.8 |
| Dec. 13 | 1311 | 1040 | 1.83 | 3.9 |
| Dec. 13 | 1321 | 1060 | 4.45 | 6.7 |

* *T*, temperature; *x*, horizontal distance along the flight-path.

### (*e*) *Heights of the Smoke Columns*

The heights of the smoke columns and associated convective clouds were determined from the theodolite observations at Mount Barker, and photographs taken there were analysed later to confirm these measurements. The results obtained are shown plotted against local time in Figure 13. The heights shown also agree well with those derived from other photographs taken at Mount Frankland (distant approximately 20 km – 12 miles – to the south) and at Mount Burnside (40 km – 25 miles – to the west). These are the greatest heights at the time and no discrimination has been made between smoke and condensed water.

Condensation levels were also estimated from the Mount Barker photographs. They were: Karara block, 1400 m; Northumberland block, 2200 m; Surprise block, 1370 m; and, as might be expected, they showed little or no variation with time.

TABLE 5

HORIZONTAL TEMPERATURE GRADIENTS: SEA BREEZE FRONTS

Date, Jan. 25, 1961

| Time | Height (m) | $\partial T/\partial x$* (°C km$^{-1}$) | $\sigma_w$ (m sec$^{-1}$) |
|---|---|---|---|
| 1458 | 240 | 0.11 | 1.0 |
| 1537 | 930 | 0.05 | 0.7 |
| 1614 | 660 | 0.08 | 0.7 |
| 1633 | 540 | 0.05 | 0.6 |
| 1734 | 920 | 0.04 | 0.8 |

* See Table 4.

Since these condensation levels were rather difficult to measure from the photographs, the values given must only be considered as "best estimates", and they may be in error by up to 100 or 200 m.

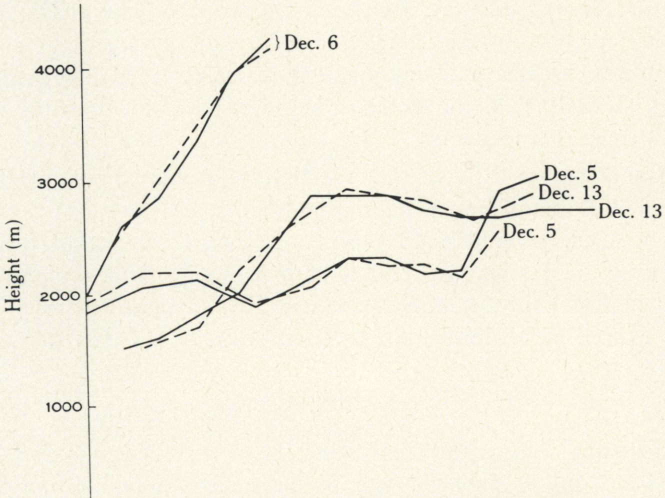

Fig. 13.–Variation with time of maximum heights of smoke column; dates as shown. Continuous lines, measured by theodolite; broken lines, measured from photographs.

### (*f*) *Ground Meteorological Stations*

Field checks of the thermohygrographs against the maximum thermometers and the Assmann psychrometer, and comparison with previous laboratory calibrations, showed that no serious calibration drifts occurred during the period of the observations. As noted above, there was only one instrument adjacent to the Northumberland block on December 6, 1969 (though of course the other two instruments continued to record at their original sites). Also, the ink on the temperature pen at site 3B dried out just before December 13, so that there are only two temperature records for that day.

As it was necessary to have the ground stations accessible by road and since a protective burn had been established around each area, this meant that the stations were up to 1 km from the fire edge. This fact, coupled with the frequent shading effect of the smoke as exemplified in Figure 9, resulted in there being no detectable changes in air temperature which could be unequivocally attributed to heat from the fires.

As might be expected on records from anemometers installed in heavily timbered country with some degree of undulation, there was a great deal of turbulent fluctuation in both wind speed and direction. Nevertheless, there were three occasions when a distinct wind change occurred at a time well correlated with fire activity.

On December 6 at site 2 a steady south-easterly wind of about 2 m $\sec^{-1}$, which showed a total range of variation in direction of about 90°, suddenly became much more turbulent about 1130 hr and the swings in direction covered the whole 360°.* This behaviour ceased at about 1630 hr and the previous steady south-east direction was resumed.

At site 3A on December 13 a steady south-east wind of about 1.6 m $\sec^{-1}$ became westerly with rather wider fluctuations about 1230 hr. This continued for some 2 hr when wild swings through the full 360° began and continued until about 1900 hr, before reverting to the steady south-east direction. On the same date at site 3C completely contrary behaviour was observed. A 2.5 m $\sec^{-1}$ wind of very variable direction, chiefly west to north-west became suddenly much more steady from a southerly direction about 1200 hr. At about 1900 hr the direction began to back slowly to the north-east with considerable reduction in velocity.

One cannot ignore the fact that the time of maximum fire intensity is not greatly different from that of maximum natural convective activity; but the suddenness of onset of these changes about midday argues strongly in favour of their being due to the fires. However, it seems likely that natural mixing processes played some part in reinforcing and sustaining the effects observed, for changes occurring as late as 1900 hr certainly cannot be attributed to the fires which in all cases subsided much earlier.

## IV. DISCUSSION

In considering the general characteristics of turbulence of the heated and unheated air as set out in Tables 2 and 3, the most striking feature is the absence of any significant difference between the general mass of the smoke and clear air at similar heights. It is only during the two traverses of December 13, 1969, when the region of intense activity directly above the fire was penetrated, that any real difference emerges.

Flight through the corresponding part of the column just above condensation level would, no doubt, have been informative, but this would have been impossible without remote positioning of the aircraft with Distance Measuring Equipment or advice from ground-based radar.

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*On occasions, the time-lapse pictures of this fire show strong vortex formation in the ascending smoke plumes. One of the films shows that, at an area on the northern side where the fire was very active from 1115 to 1130 hr, local winds at the edge of a rotating column of smoke some 800 m in diameter were of the order 12 m $\sec^{-1}$ (25 m.p.h.).

The air in the upper levels around the fires of December 5 and 13, though having shallow stable layers, showed on the whole a fair degree of instability. On December 6 there was conditional instability (i.e. instability with respect to saturated ascent) from condensation level upward, and the smoke from this fire rose to a considerably greater height. It is obvious that atmospheric instability must be one of the most important factors governing the development of a blow-up fire on a hot summer's day. Indeed, the similarity of the meteorological parameters associated with a large fire to those producing severe thunderstorms and tornadoes has been noted by Taylor and Williams (1967, 1968).

The very large maximum rates of heat input shown in Table 1 are an order of magnitude greater than those which would be expected of natural solar heating at this latitude and season, and should be compared with the values of about 2 cal $\text{cm}^{-2}$ $\text{min}^{-1}$ characteristic of the milder control fires investigated by Taylor *et al.* (1968). These large heating rates are consistent with the strong baroclinicity near the edge of the smoke just above the fire area. (Cf. the figures for horizontal temperature gradients on December 13 in Table 4). Comparison with the corresponding figures for December 5, 1969 and December 6, 1969 in Table 4 (and also with the observations on sea breeze fronts in Table 5) suggest that there is a strong effect on the intensity of turbulence only when the baroclinicity is large; in other circumstances $\sigma_w$ is no doubt controlled by the more usual variables – static stability, wind shear, and so on. The fact that the largest values of $\partial T/\partial x$ and of $\sigma_w$ were observed on the day with the lowest heating rate (December 13) is simply a result of the sampling procedure followed: as noted above, flight through the most intense part of the fire was not attempted until evidence had accumulated that it would be safe to do so.

In Figures 10–12 the lines *CD* are dry adiabatics drawn so as to enclose, with the environmental temperature distribution *AB*, an area equivalent to the total heat input from the fuel quantities shown in Table 1. The points *D* would then predict the height to which the smoke columns would rise if there were no entrainment* of air from outside, and no condensation. (Loss of heat by radiation is negligible – see, for example, Taylor *et al.* 1968.)

However, a more meaningful calculation of total heating is made by starting from the point *B* (where the temperatures inside and outside the smoke are presumably equal), inserting a saturated adiabatic down to condensation level, and then a dry adiabatic down to the surface. These lines are shown by *BFE* in the figures. In the case of Figures 10 and 12, the saturated adiabatic lapse rates calculated at condensation level and at the top of the column were so nearly equal that a mean value could be taken; but in Figure 11, the value at the top of the column has been used for the upper half, and that at condensation level for the lower half of the saturated layer.

The areas enclosed between *EFB* and *AB* are taken as reasonable approximations to the heat contributed to the smoke columns by the fires, and are smaller than those attributable to the amounts of heat available; the ratios between them must represent the degree of dilution by the outside air, that is, the entrainment factor. These ratios are: December 5, 2.9; December 6, 5.9; December 13, 2.5. However, the fires all rose to different heights and the mean entrainment rate is 1.037 per 100 m with standard error of the mean 0.002 per 100 m. That is, the entrainment factor over a height

*The word "entrainment" will be used to mean all dilution of the smoke column by exchange of air between the smoke column and environment, whether by inflow or turbulent diffusion.

interval of 200 m is $1.037^2$, and so on. The entrainment rate on December 6 was 1.042 per 100 m compared with 1.035 on each of the other two days. This difference can hardly be regarded as significant, but is in the expected sense because the much greater instability on December 6 caused the column to rise much more rapidly (see Fig. 13), and this more violent vertical motion could well have been associated with more intense mixing.

When the convection column rises above condensation level, latent heat is released and the convection process acquires a new source of energy. It would be of interest to know the fuel equivalent of the latent heat, though it is difficult to define exactly what is meant by this. It is here taken to mean the additional energy which would have been required to raise the smoke column to the same height as that observed, if the convection had been controlled entirely by unsaturated processes. An estimate of this additional energy is given by the area between *FB* and an extension of *EF* in Figures 10–12, and the corresponding fuel amounts for the three fires respectively are 1.4, 2.3, and 1.1 tons per acre. Dilution by ambient air, however, increases the mass of air actually heated above what it would have been in the absence of entrainment. Thus these fuel amounts must be multiplied by entrainment factors for those parts of the fires above condensation level which, from the *mean* entrainment rate given above, can be estimated approximately as 1.8, 2.1, and 1.6. The final fuel equivalents are 2.5, 4.8, and 1.8 tons per acre, corresponding to latent heat contributions over and above the actual fuel amounts as shown in Table 1, viz. 6.0, 5.3, and 5.0 tons per acre.*

The calculations described above give some basis for predicting the height to which fires will rise; however, they make use of one datum which would not usually be available before a fire was lit – the observed condensation level. It is useful, therefore, to see with what accuracy condensation levels can be predicted from observations made on the ground. Readings of temperature and humidity were taken from each of the three thermohygrographs† for the 10 half-hourly observations from 1030 hr to 1500 hr – chosen as a period when the lower layers of the atmosphere might be expected to be reasonably well mixed, on a day when the weather is conducive to the development of intense fires. Dew points were calculated, and then the condensation levels, i.e. the heights to which surface air would have to be lifted at the dry adiabatic lapse rate, to make the actual temperatures equal to the dew points. The values obtained for the three fires in turn are 1340 m (observed 1400 m), 1820 m (2200 m), and 1210 m (1370 m). The standard deviations of a single calculated value are 90 m, 240 m, and 150 m, and the standard errors of the means are 20 m, 40 m, and 30 m.

The accuracy with which the condensation level can be estimated is of interest only in the context of predicting the height to which a smoke plume will rise – that is, of predicting the course of the line *EFB* in Figures 10–12, given the environmental lapse rate and making suitable allowance for entrainment.

For the fires of December 5 and 13 this prediction can be made directly on a temperature/height graph. (The fire of December 6 must be treated differently because of the conditional instability which occurred, and it will therefore be discussed separately.)

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* It should be noted that the water produced as a result of combustion amounts to about 0.1 g $\mathrm{cm}^{-2}$. A reasonable estimate of water in the atmosphere above the fire to a height of 3000 m – including that brought in by entrainment – would be about 5 g $\mathrm{cm}^{-2}$: thus the effect of water from combustion on the dynamics of the fire is negligible in comparison.

† Two only on December 13, 1969 when the temperature pen had dried out.

The environmental lapse rate is plotted, and the predicted condensation level is inserted. Various heights for the top of the fire are then assumed, and the corresponding lines *BFE* (starting from *B*) are drawn in. Fuel quantities corresponding to the enclosed areas are multiplied by the entrainment factors appropriate to the assumed heights, these being derived from the mean entrainment rate of 1.037 per 100 m. The figures so obtained are then compared with the fuel quantity actually available and, by interpolation, the predicted height is found.

For the fires of both December 5 and 13, the height predicted is 2700 m, in comparison with observed heights of 3000 and 2500 m respectively. If entrainment and condensation are neglected, the predicted heights (points *D* in Figures 10 and 12) are 2750 m and 2500 m. Thus, on the two days when we can compare them, the more elaborate calculation, allowing for entrainment and condensation, shows up as only slightly better than the simpler one; however, for the fire of December 6, point *D* predicts a height of 3000 m, which, in comparison with the observed height of 4300 m, cannot be regarded as satisfactory.

For the fire of December 6, entrainment cannot be treated in the simple way outlined above. When the data of Figure 11 are replotted on an aerological diagram having coordinates (for example) temperature and the logarithm of pressure, it becomes clear that at the point *G*, where the ascending air becomes cooler than its environment, sufficient kinetic energy has been accumulated to carry the convection up at least as far as *B*. But, at *B*, the ascending air would once again become warmer than the environment and there would be no reason why the convection should not continue higher. There is a standard method of allowing for entrainment on an aerological diagram (see, for example, Haltiner and Martin 1957), and this has been applied in the present case to re-assess the lapse rate of the rising air above condensation level. Dewpoints from the radiosonde ascent at Albany (flight commencing at 0715 hr local time) have been used as a measure of the water content of the environmental air, and heights have been converted to pressures according to the standard I.C.A.N. atmosphere.* The resulting lapse rate is about 8.2°C km$^{-1}$.† When this lapse rate is used above the calculated condensation level, and entrainment below is treated as in the fires of December 5 and 13, then the predicted height of the top of the smoke column is 3740 m. This figure is in reasonable agreement with the observed height of 4300 m.

## V. CONCLUSIONS

With fires of area a few tens of square kilometres and whose smoke columns reach heights of 3000–4000 m, there is evidence that severe turbulence, sufficient to cause a hazard to aircraft, may occur in the smoke column immediately above the fire at heights up to about 1 km, before it begins to spread out. (It must be remembered that the present measurements were made at the low airspeed of 85 knots which would have minimized turbulence effects.) However, in other parts of the heated air

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*This is legitimate since heights were measured by the aircraft altimeter calibrated according to this standard, and the sea level pressure at the time was close to 1013 mb.

†It must be pointed out that the calculation is not of high accuracy; existing aerological diagrams, designed to be used over a much greater depth of atmosphere, have a very small scale for the present application.

(except possibly immediately above condensation level, where the convection takes on new impetus owing to the release of latent heat), the effects of turbulence on aircraft would be no more than moderate.

There is good evidence of marked inflow of air from all directions into such fires, up to heights of at least 300 m: and the consequent strong updraft in the core of the fire has been observed at about 1000 m. In the present experiments no heating of surface air by the fires could be detected at distances of about 1 km from the fire edge, though cooling due to shadowing by the smoke was frequently observed.

Entrainment of environmental air into the vertical smoke column was estimated to be at the rate of 1.037 per 100 m, with good consistency. Using this entrainment rate, and a condensation level as calculated from surface observations, it is possible to predict the height to which a fire will rise in the absence of conditional instability. Though results obtained in this way are quite good, a rougher estimate neglecting both entrainment and condensation is only slightly worse.

When conditional instability is present it is necessary to use standard methods of allowing for entrainment, as given in meteorological textbooks. When this is done a satisfactory estimate of fire height is obtained.

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