Wind Information Prediction Study: Annaburroo Meteorological Data Analysis

A.M. Durre and Tom Beer

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Table of Contents

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A.M. Durre and Tom Beer
CSIRO National Bushfire Research Unit
Private Bag 1, Mordialloc, Vic. 3195

Abstract

During August 1986, the National Bushfire Research Unit conducted experiments in the Northern Territory to study the spread of fire in grasslands. The wind speed at various heights is an input variable to the fire meters used to predict the spread rate. Six methods of vertically extrapolating the wind speed were examined and tested against a data set from anemometers near the fires.

The skill scores for the ability of these methods to predict the wind-speed at mid-flame height ranged from a low of 0.7, when a constant ratio of 10 m to 2 m wind is used, to a high of 0.98, when a surface-layer wind speed profile and accurately quantified atmospheric stability are used.

1 Introduction

During July and August 1986, the National Bushfire Research Unit (NBRU) conducted field experiments on the spread rate of fire in tropical grasslands. The experiments were designed to test the performance of various fire danger meters when used outside the area in which they were originally calibrated. The meters that were tested were the McArthur fire danger meter and the Rothermel meter. These meters require inputs of both fuel and weather, with wind speed and fuel moisture being the key variables. They produce estimates of the spread rate of the fire front, and this spread rate is directly related to the fire danger.

Prior to the experiment, an area of flat grassland near Annaburroo of approximately 4 km square was subdivided into blocks, either 100 m or 200 m square. Different fuel treatments were applied to these blocks. For example, some blocks were mown and the grass scattered back onto the block. The actual experimental runs began by igniting the grass along a corner or edge strip, chosen so that the wind would carry the fire in each block for the maximum possible distance. The rate of spread was measured from aerial photographs.

The meteorological variables used in the relevant fire danger meters are the temperature, relative humidity and wind speed. Though the temperature and relative humidity are direct inputs into the McArthur Mk4 fire danger meter, they act as surrogates for fuel moisture, which is the required variable in the McArthur Mk5 and Rothermel meter. Furthermore, the different models require different wind speeds. The McArthur meters, having been based on field calibrations in south-eastern Australia, expect 10 m wind speeds. The Rothermel model, having been partially calibrated on the basis of wind-tunnel tests, requires the wind speed at mid-flame height. During the Northern Territory Grasslands Fire Experiment experienced fire researchers continually recorded their visual estimates of the flame height.

The choice of meteorological variables that were measured, and the locations at which they were recorded, were governed by the primary objective of the experiment, namely to test the performance of the above-mentioned meters. This was done by maintaining a central meteorological station (Metsite) and also by measuring winds as close to the fire as possible. Details are given below.

The objectives in the data analysis were:

- To validate the meteorological data by testing its accuracy and reliability, and
- To test methods for predicting the winds at an arbitrary height above a fire front, in flat grassland up to 4 km from the central meteorological station.

This report thus serves a dual purpose. It is a report on the method of meteorological data collection, verification and analysis used for the Northern Territory Grasslands Fire Experiment. It also reports on the results of different methods of predicting the wind at mid-flame height from the wind at 10 m height. Because this report is written for the user community of fire researchers, who may be expected to deal with such data despite a lack of formal meteorological training, we have included substantial detail on the instrumentation and methodology.

2 Instrumentation and data gathering

A number of boundary-layer meteorological experiments have been conducted in Australia over the past two decades. These include several micrometeorological experiments at Hay, N.S.W. and Kerang, Victoria described e.g. by Swinbank (1964, 1968) and Swinbank and Dyer (1968), the Wangara Experiment (Clarke et. al., 1971) at Hay, N.S.W. during July-August 1967, the Koorin Expedition (Clarke and Brook, 1979) at Daly Waters, N.T. during July-August 1974 and the International Turbulence Comparison Experiment (Garratt et al., 1979, Dyer et al., 1981) at Conargo, N.S.W. during October 1976.

The results of these experiments greatly increased our understanding of boundary-layer structure, and the conduct of those experiments established optimum standards necessary for high-quality field observations. Such standards include calibration of all instruments both before and after the experiment, with spot checks, if possible, during the course of the field-work. On-site access to preliminary results is valuable because analysis of these data may indicate potential instrument malfunction, and if this can be corrected in the field then useful data may still be retrievable. Data analysis should be undertaken as soon as possible for the same reason. Simple micro-meteorological reasoning indicates, for example, that the mean wind at 10 m exceeds the mean wind at 2 m, and that the potential temperature difference should change sign at dusk and dawn.

The vertical structure of the mean wind is given by

$$U = \frac{U_*}{k} \ln\left(\frac{z-d}{z_0} - \psi\right) \qquad (1)$$

where k is the von Karman constant (0.40), U_* is the friction velocity, z is the height above ground (in this report, all heights are given as above ground), d is the height of the zero-plane displacement, z_0 is the roughness length and ψ is a mathematical function that incorporates departures from the logarithmic wind profile that arise when the atmospheric stability is not neutral.

Extrapolating the vertical profile of the mean wind requires information on atmospheric stability. The micro-meteorological measurements needed for atmospheric stability calculations are wind speed and temperature at a minimum of two heights near the surface. At the Annaburroo central meteorological instrument site (the Metsite), wind speed was measured at 2 m using a sensitive-cup anemometer designed for measuring winds around the fires, and at 10 m using the UNIDATA anemometer that is provided as an accessory to the data loggers. The temperature at 2 and 10 m was measured using solid-state temperature probes that were shielded and aspirated Analog Devices type AD537 with a 2B57 encapsulated pre-amplifier.

A portable Clarke mast was erected each day at a location as near to the planned location of the fires as possible, while remaining upwind of them. Winds were measured at 2 and 10 m using sensitive-cup anemometers. The Clarke mast locations were from 0.5 to 1.5 km from the Metsite and were located in grass blocks sufficiently far downstream not to be influenced by clumps of trees.

Around each fire, four sensitive-cup anemometers measured wind speed at 2 m height every 5 seconds. The fire anemometers were switched on some minutes before burn time, switched off some minutes after the burn and then moved to a new location.

At the Metsite, the relative humidity (R.H.) was measured with a Phillips Humidicap sensor. A solarimeter measured the downward radiation. Wind direction was only measured at 10 m at the Metsite, using a UNIDATA wind vane which produced two component voltages.

On seven of the fifteen burn days, vertical temperature readings were taken every 150 m from the ground up to about 1400 m. Measurements were taken using a helicopter with an Aspen psychrometer or the helicopter temperature probe. The temperature data were plotted on an aerological diagram. On most days, the data reveal a superadiabatic layer near the ground up to about 150 m, a well-mixed layer aloft to about 800 m and an inversion above that. The temperature was converted to potential temperature θ by the formula

$$\theta = T + 0.0098z \tag{2}$$

where z is the height of the reading in metres, and the constant is the adiabatic lapse rate in degrees Kelvin per metre. Figure 1 is a plot of the potential temperature vs. height for each of the days that data was taken. The temperature readings have fairly large errors ($\approx$ 1 to 2°C) due to problems in properly aspirating the psychrometer with ambient air or due to the coarse readings on the aircraft temperature probe. Because of these problems, the data were not used in any further analysis. The raw data were gathered from the Metsite, the Clarke mast and the fire anemometers using UNIDATA dataloggers and downloaded into an IBM-PC compatible computer. Initially, the Metsite datalogging was to have been done using an LSI-11 computer, but this had a failure at the experimental site, and became unusable. Preliminary processing for initial inspection was carried out at Annabur-

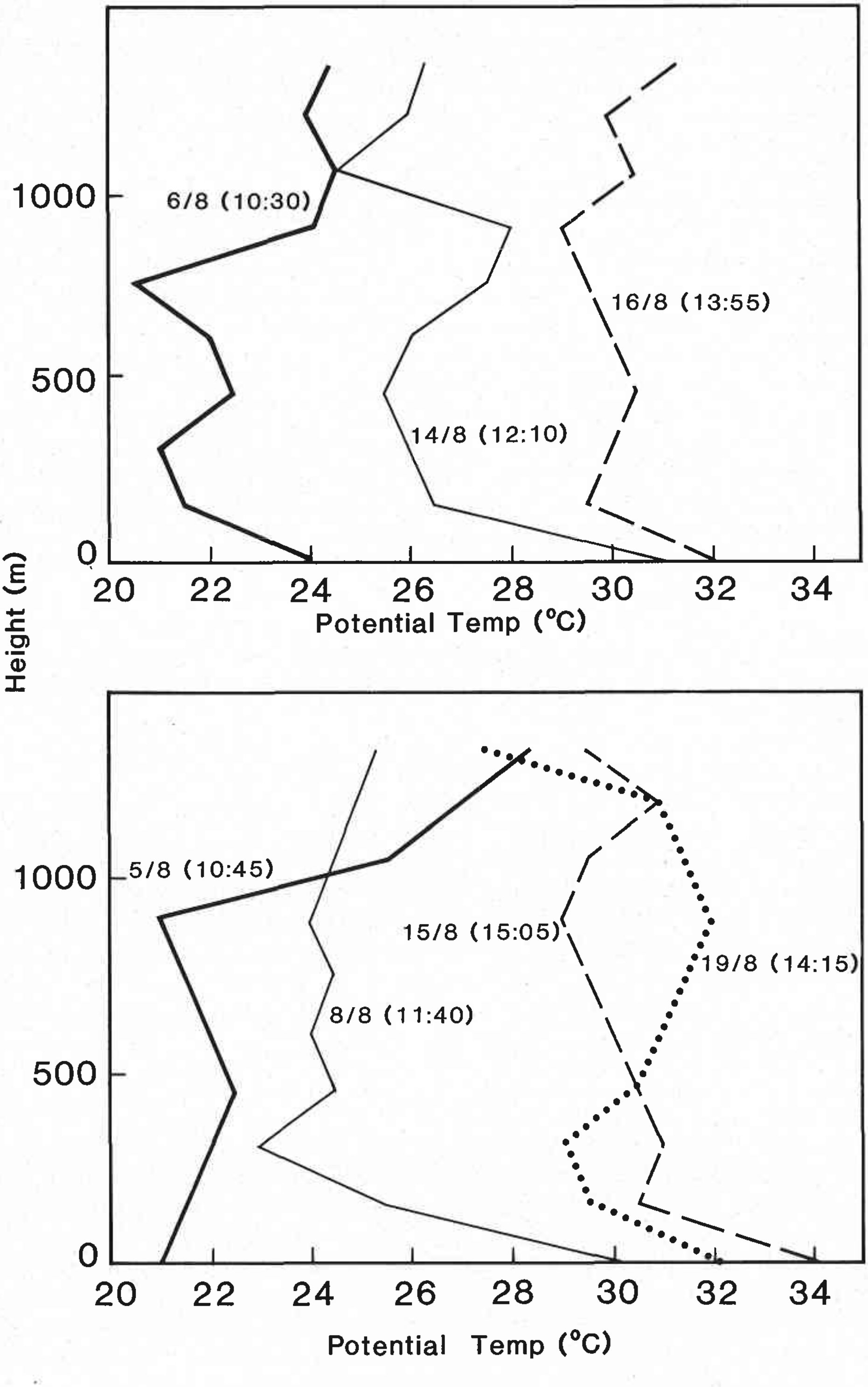

Figure 1: Daily Vertical Potential Temperature Profile

roo and the raw data were put on floppy disks for further processing. All times are in Central Standard Time (GMT +9 hr 30 min).

3 Instrument calibration

Calibration of the anemometers over the range 0 to 15 m s^{-1} was done in a wind tunnel both before and after the experiment. All the sensitive cup anemometer calibrations were compared and found to be sufficiently similar to each other that mean regression parameters could be used with no significant loss of accuracy. The worst-case deviation of the individual calibrations from the average calibration was only 0.05 m s^{-1}, at 1 count s^{-1}. A re-calibration was also done on the UNIDATA 10 m anemometer in the CSIRO Division of Atmospheric Research wind tunnel at Aspendale.

The temperature probes were calibrated in a temperature-controlled oil bath over the range 20 to 40°C. In the original data analysis, the temperature probes had been calibrated in the field against thermohygrograph readings because of the problems with the LSI-11 computer, and these regressions were, of necessity, only approximate. This showed up in the original analysis as positive potential temperature differences during the middle of the tropical day, a very unlikely situation. A re-calibration in June, 1987, using temperature-controlled oil baths, produced more realistic temperature differences. Results using this re-calibration were checked using the data collected on the 14 August 1986, when the Metsite instruments were left on until an hour after dusk. The requisite transition of the potential temperature differences, from negative to positive at dusk, confirms the data reliability. The accuracy of the probes is about 0.1°C.

The relative humidity (R.H.) sensor was calibrated against field readings using an Aspen psychrometer, from which the R.H. at the fuel sample times was calculated just before the burns. The accuracy of the sensor is about ±3% in R.H.

The solarimeter (pyranometer) was calibrated by using the maximum recorded value on cloudless days. Taking the latitude of Annaburroo as 12° 55′S, the solar declination on the central day of the field trip as 15° 05′N, we obtained a minimum solar zenith angle of 28°, for local noon. The formula for finding the insolation is

$$I = J_0 A^{\sec\Theta} \cos\Theta \tag{3}$$

(List, 1984 p.420), where the solar constant $J_0 = 1.358$ kW m^{-2}, (List, 1984 p.414), Θ is the zenith angle of the sun and A is the atmospheric transparency. Using a value of 0.85 for A (List, 1984 p.420), we obtain the maximum possible value of the insolation I_{max}:

$$I_{max} = 0.995\,\mathrm{kW\,m^{-2}} \tag{4}$$

The smoothest data curve was on 19 August, with a maximum reading of 5700 counts min^{-1}. Assuming the response is linear, we can check that the counts go to zero at no light conditions, e.g. on 14 August after sunset. When the curve of the insolation is very irregular then it is possible to have values above the noon maximum. This is caused by bright clouds, and under these conditions we obtained values up to 1.25 kW m^{-2}. The accuracy of pyranometers is usually 5 to 10% in absolute value and about 1% in linearity.

Problems with the LSI-11 computer, originally planned for downloading the information from the central data logger, led to all instruments being rewired and readjusted to the UNIDATA data logger. With instruments that produce a voltage output, this meant that the original calibration curves were no longer valid, so only post-experiment calibrations were used. Full micro-meteorological measurements were not started until 4 August, which meant that three burn days i.e. 30 July, 31 July and 1 August are not covered in this data analysis. Solarimeter data were not gathered for the first four days; i.e. 4, 5, 6 and 8 August.

4 Conversion formulae

For the sensitive cup anemometers, the calibration data were fitted by two regression lines. At less than 5 counts s^{-1}, the calibration was

$$U = 0.5637C + 0.1452 \tag{5}$$

At greater than or equal to 5 counts s^{-1}, the calibration was

$$U = 0.4921C + 0.4705 \tag{6}$$

These curves do not meet exactly at $C = 5$, but the error is less than 0.03 m s^{-1}. The use of mean values for the calibration parameters for all the anemometers will produce a maximum of 0.05 m s^{-1} deviation of any reading from the individual calibration.

For the UNIDATA anemometer

$$U = 0.1387C + 0.24 \tag{7}$$

For the temperature probes

$$T_1 = 0.228C_1 - 17.714 \tag{8}$$

for the 2 m probe, and

$$T_2 = 0.230C_2 - 18.534 \tag{9}$$

for the 10 m probe. For all these regression lines, we have $r^2 > 0.99$. For the solarimeter

$$I = 0.95C \tag{10}$$

For the R.H. sensor

$$RH = 0.771C - 5.399 \tag{11}$$

with $r^2 = 0.95$. For the wind direction

$$D_S = \frac{255 - C_S}{127.5} - 1 \tag{12}$$

$$D_W = \frac{255 - C_W}{127.5} - 1 \tag{13}$$

$$D = \arctan\left(\frac{D_S}{D_W}\right) \tag{14}$$

where

- C, C_1, C_2, C_S, C_W are the various channel counts per second,
- U is the wind speed in m s^{-1},
- RH is the relative humidity in percent,
- T is the temperature in degress Centigrade,
- I is the insolation in mW cm^{-2} ,
- D_S, D_W are the wind direction components,
- D is the wind direction from north, and
- r is the correlation coefficient.

5 Data processing

The Metsite and Clarke mast data were recorded at one minute intervals, usually from 0900 to 1630 hours each day, on the 11 burning days that had complete data. On 30 and 31 July and 1 August, the Metsite was not in full operation and the Clarke mast was not located near the burning sites. On the data logger, the time was recorded to the second. We wished to synchronize the readings from the two data loggers, so the Metsite and Clarke mast data were interpolated to the minute mark from the second reading.

The individual files of data for each fire anemometer were combined into one file for each day, after the data were similarly interpolated to the 5 second mark, starting on the minute. The first line of the file of fire anemometer data contains the date and start time hour and minute.

6 Profile calculation

To predict the mean winds at any height, we need to know the form of the atmospheric wind and temperature profile near the ground. The integrated forms of the similarity profiles are:

$$\Delta U = U(Z_2) - U(Z_1) = \frac{U_*}{k} \int_{Z_1}^{Z_2} \frac{\phi_M}{Z} dZ \qquad (15)$$

$$\Delta \theta = \theta(Z_2) - \theta(Z_1) = \frac{\theta_*}{k} \int_{Z_1}^{Z_2} \frac{\phi_H}{Z} dZ \qquad (16)$$

where

- $U(Z)$ is the mean wind at height Z,
- $\theta(Z)$ is the potential temperature at height Z,
- ϕ_M, ϕ_H are the non-dimensional wind and potential temperature gradients, which are functions of the dimensionless parameter, Z/L, where L is the Monin-Obukhov similarity length,

- Z_1, Z_2 are the two heights,
- U_*, θ_* are the turbulent friction velocity and temperature scales,
- k is von Karman's constant = 0.40.

The solutions to these formulae are discussed in Appendix A.

The vertical wind profile is needed because the Rothermel model is based on the wind speed at mid-flame height, whereas it is standard Australian Bureau of Meteorology practice to measure wind at 10 m height. Thus the mean wind at mid-flame height at a fire some distance from the central Metsite needs to be estimated on the basis of the 2 m and 10 m mean wind speeds and temperatures at the central Metsite. This was done by assuming that the Monin-Obukhov length and the drag coefficient $C_{D,Z}$ are the same at the central Metsite and at the fire-front. The drag coefficient, $C_{D,Z} = (U_*/U(Z))^2$, is a parameter which depends on the reference height, Z, the surface roughness and the Monin-Obukhov stability function. This assumption will be valid because there were no significant changes in slope (the site was flat) or surface roughness (the site was grassland).

The profile variables are calculated using the 30 minute running means of U_2, U_{10}, T_2 and T_{10}, where the subscripts 2 and 10 refer to 2 m and 10 m heights, respectively. On the 8 August, there were problems with the Metsite 2 m anemometer, so the Clarke mast wind speeds were used in the calculation. The mean and standard deviation of the wind direction are calculated using the method of Fisher (1983), and the robust Richardson number (RI), the friction velocity and the drag coefficient are also calculated. In the unstable case (the overwhelming majority of the time), $1/L$ is calculated using the method of false position (Regula Falsi) with reasonable initial guesses (Abramowitz and Stegun, 1964, p.18). For the stable case an analytic expression using the Richardson number is used directly (Webb 1970). Running means of the insolation and R.H. data were also calculated. As can be seen from Figure 9, $1/L$ is always negative during the day and tends to be small at the beginning and end of the day, and larger in the hottest part of the day. The expected transition to night-time stability is seen in the data for 14 August. These calculations are also described in Appendix A.

7 Zero-plane displacement

Before the formulae can be used to deduce wind speeds, an estimate of the zero-plane displacement is needed. This problem has been tackled by a number of authors (Stearns, 1970; Lo, 1977, 1978, 1979; Nieuwstadt, 1978) who offer various solutions depending on the combination of available meteorological information. This work follows these authors, but is concerned with the specific case of vertical wind prediction when the available information consists, at the most, of wind speed and temperature at two heights.

The heights Z_1 and Z_2, in the profile forms given above, are not the actual heights above solid ground, but are modified by the zero-plane displacement by the formula

$$Z = z - d \tag{17}$$

where z is the actual height and d is the zero-plane displacement. This comes from the roughness elements close to the ground, and is usually taken to be (Brutsaert, 1982)

$$d = 0.64H \text{ to } d = 0.75H \tag{18}$$

where H is the average height of the roughness elements. We will use a factor of 0.75 in this report. The Metsite was a bare earth clearing. The zero plane displacement, d, was taken to be 5 cm. This value was seen to be reasonable when a simple log profile was fitted to the data at neutral stability on the 14 August. At the Clarke mast, d was estimated from the grass height information and the upwind block photographs, the grass height usually being about 0.7 m to 0.9 m.

Associated with the aerodynamic nature of the surface is a parameter z_0, the aerodynamic roughness length, which appears in the integral form of the profile as the height at which the wind speed goes to zero. This is about 0.1 to 0.2 of the value of the zero-plane displacement (Garratt, 1977), and on this basis at the Metsite, was about 5 to 10 mm. This value is usually calculated from wind runs at neutral stability, but this was not possible owing to a lack of data. In the calculations given herein, we will use a value of 5 mm, i.e. a ratio of 0.1.

8 Daily weather variables

From the data, we can examine the daily weather variables.

- Wind speeds. These varied between 2 and 8 m s^{-1}, peaking between 1000 and 1200 hours.

- Temperatures. These varied between 20 and 35°C, with a daily maximum between 1500 and 1630 hours each day.

- Wind directions. These were usually in the NE to SE quadrant, although on three days, i.e. 8 August, 14 August and 16 August, these were from significantly different directions.

  - 8 August. After a 'standard' pattern, the wind veered from SE to SW to W after about 1345 hours.
  - 14 August. The wind was mainly southerly until about 1500 hours, then backed to the east, until 1700 hours, when it veered south.
  - 16 August. The wind started out NE and slowly backed to NW during the day.

- Relative Humidity. The minimum relative humidity was usually between 18% and 30%, at the time of the daily maximum temperature. On 17 August, the minimum R.H. was approximately 45%, quite high for the location and time of year.

9 Graphs of the data

To illustrate the data set, a 'representative' day, 19 August, has been chosen. The running means of the measured variables, and the parameters resulting from the calculations described above and in Appendix A, have been plotted. These plots are shown in Figures 2 to 14. The data follow the trends indicated above. The potential temperature difference between 10 m and 2 m is typically about 1°C, reducing as the sun goes down. The Monin-Obukhov length varies from about -20 m to -1 m. In particular, the linear relationship between $1/L$ (at constant Z) and the Richardson number (RI) is clearly illustrated. The insolation curve was relatively smooth on this day, with some dips in cloudy periods.

10 Wind prediction

We can now predict the 1 minute averaged 2 m Clarke mast wind from the 1 minute averaged 10 m wind, using the profile variables. The drag coefficient and Monin-Obukhov lengths calculated at the Metsite are applied to the Clarke mast 10 m wind to calculate a 2 m wind speed, and the means and standard deviations of both the absolute and relative difference between predicted and observed wind speeds are calculated, as well as the skill score, and are given below in Table 1. The values for the date 8 August are not given, due to problems with the Metsite 2 m wind speed measurements. In the following tables:

- ZPD is the zero-plane displacement in metres,
- <U> is the predicted wind speed in m s^{-1} at 2 m,
- U is the measured wind speed in m s^{-1} at 10 m, and
- σ is the standard deviation of the difference measures over the whole data set.

The skill score is the square of the correlation coefficient between the expected and observed values, and is calculated from

$$\text{Skill} = 1 - \frac{\Sigma(< U > - U)^2}{\Sigma U^2} \tag{19}$$

The persistent positive value for $< U > - U$ indicates that there is a consistent over-prediction of the wind speed. This is caused by using 5 cm for the zero-plane displacement; a value that is valid for the Metsite. More realistic estimates of the ZPD were obtained by estimating the vegetation heights from the field observations on each block and the upwind block photos for the Clarke mast location, for each day of the data. When these are used, the results are as given in Table 2. These calculations reduce the over-prediction. Other reasons for the small remaining over-prediction could be disturbance of the profile by trees etc. (fetch effects) and errors in the wind speed and temperature measurements.

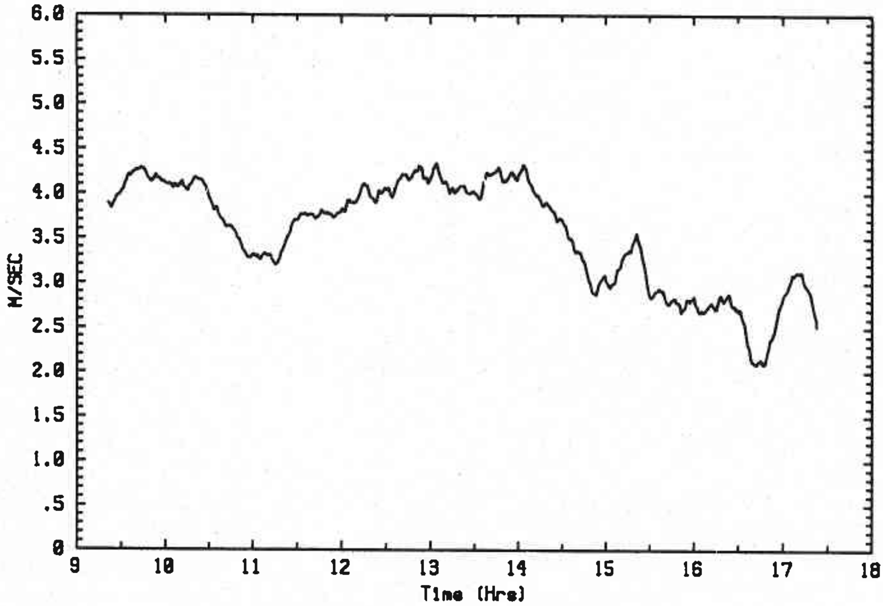

Figure 2: 2 m wind speed on 19 August 1986 (30 min. running means)

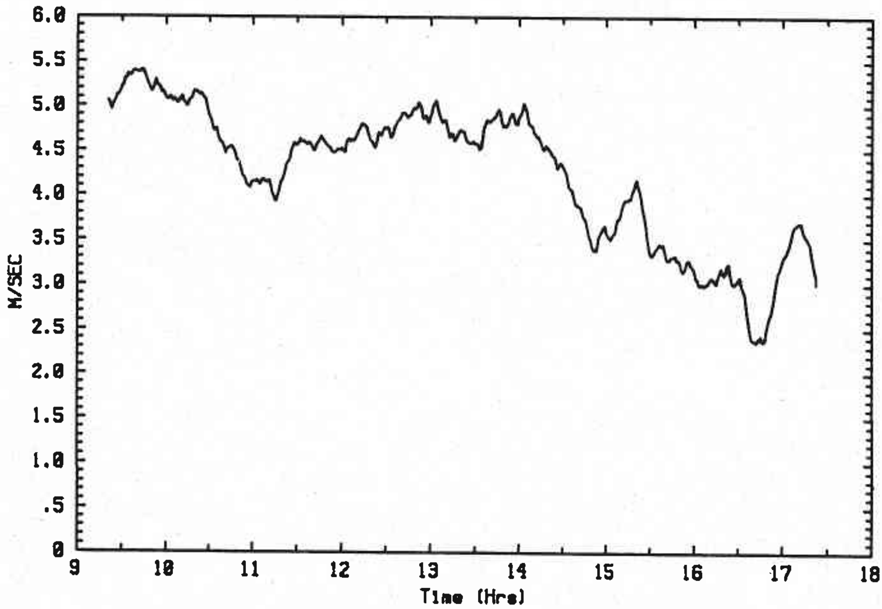

Figure 3: 10 m wind speed on 19 August 1986 (30 min. running means)

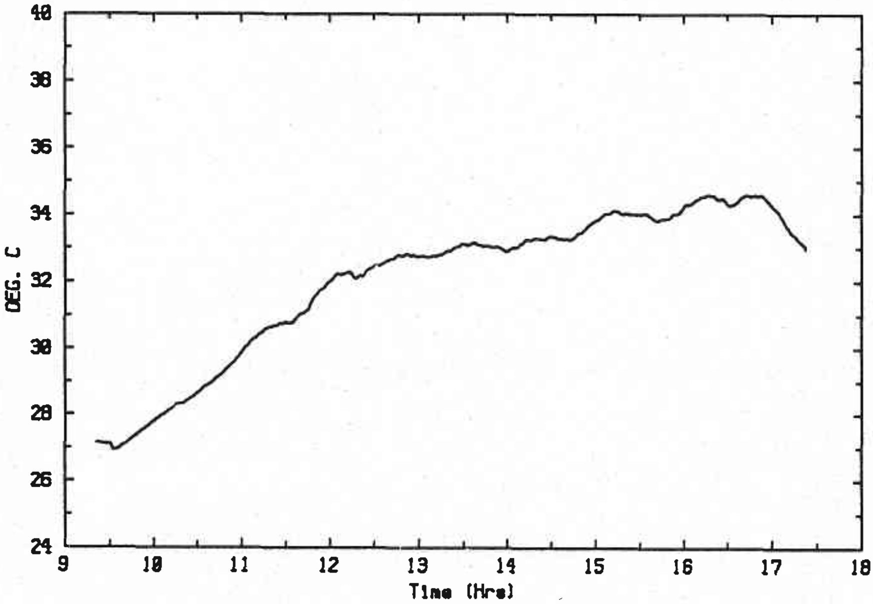

Figure 4: 2 m temperature on 19 August 1986 (30 min. running means)

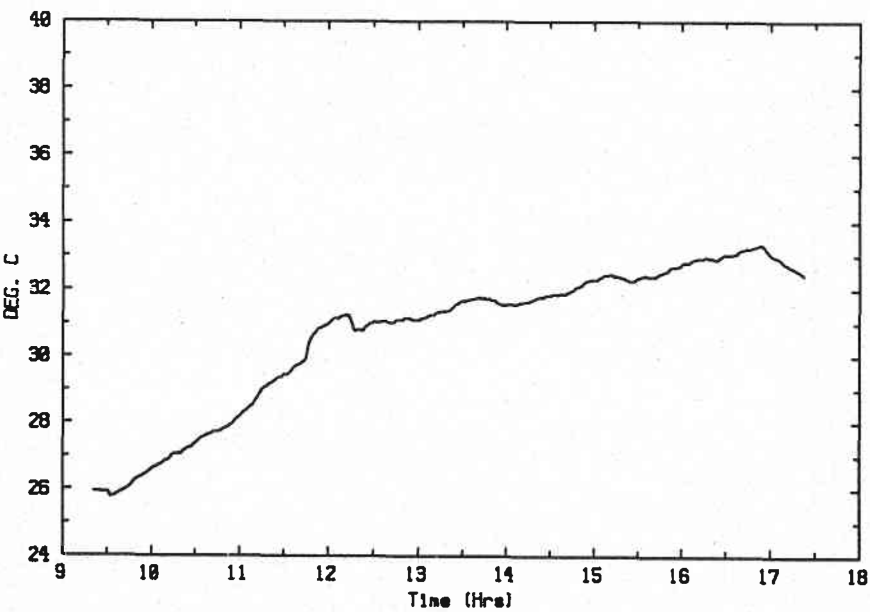

Figure 5: 10 m temperature on 19 August 1986 (30 min. running means)

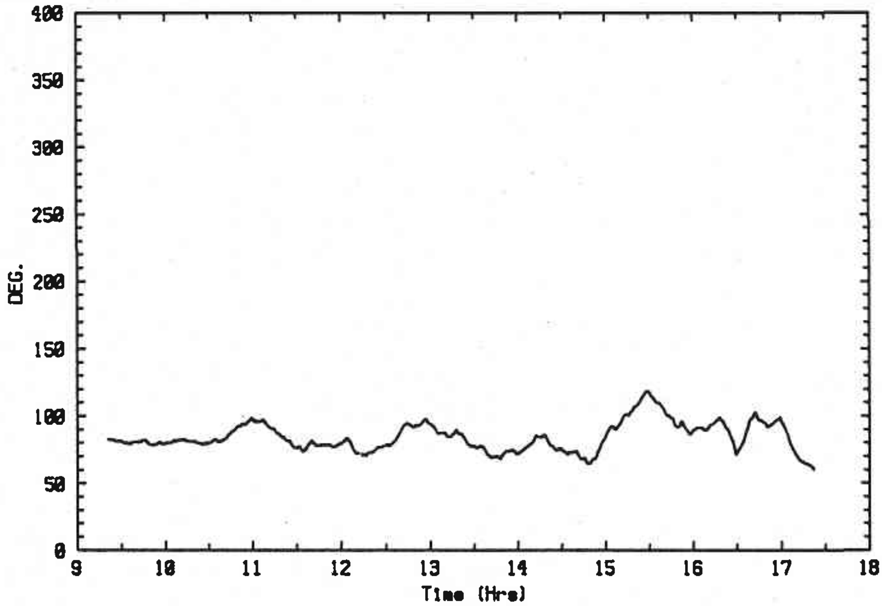

Figure 6: 10 m wind direction on 19 August 1986 (30 min. running means)

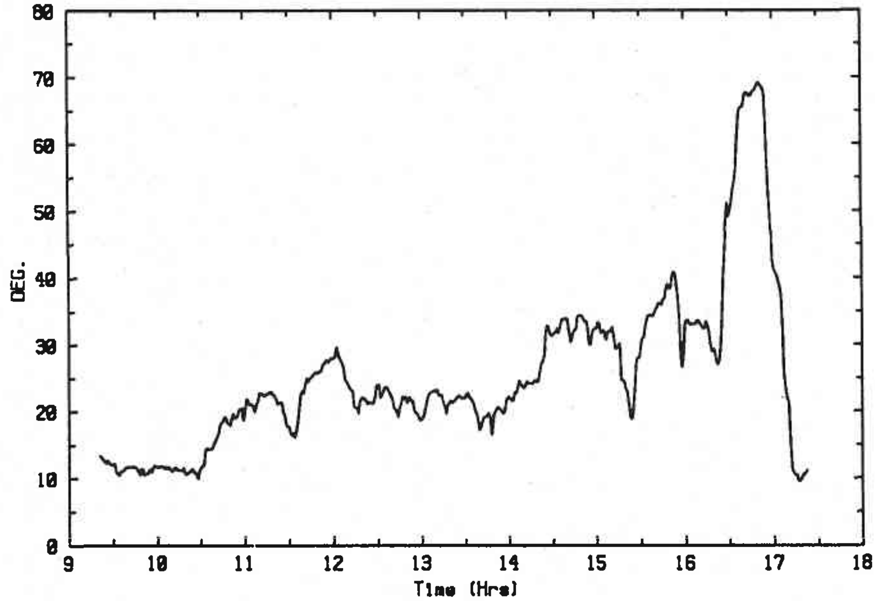

Figure 7: 10 m wind direction standard deviation on 19 August 1986

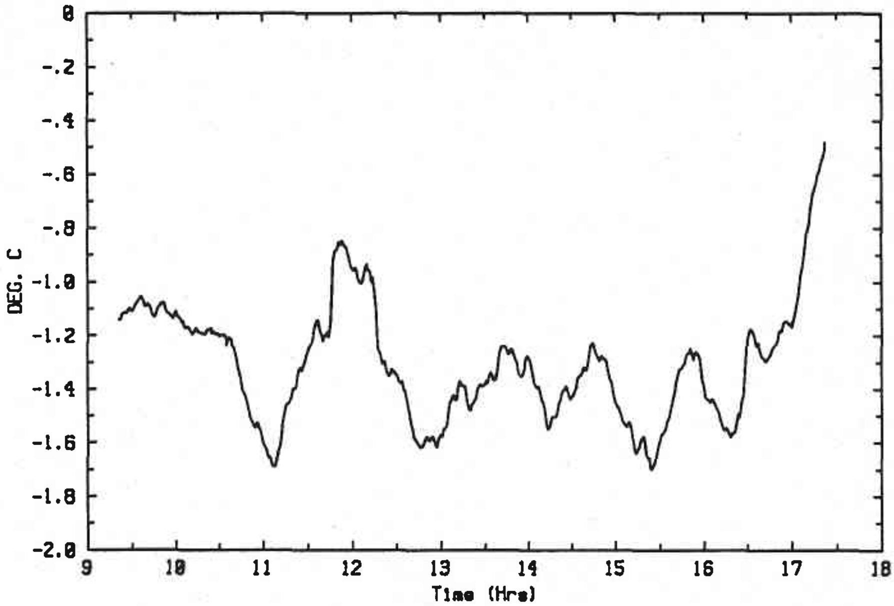

Figure 8: Potential temperature difference $\Delta\theta$ (10 m - 2 m) on 19 August 1986

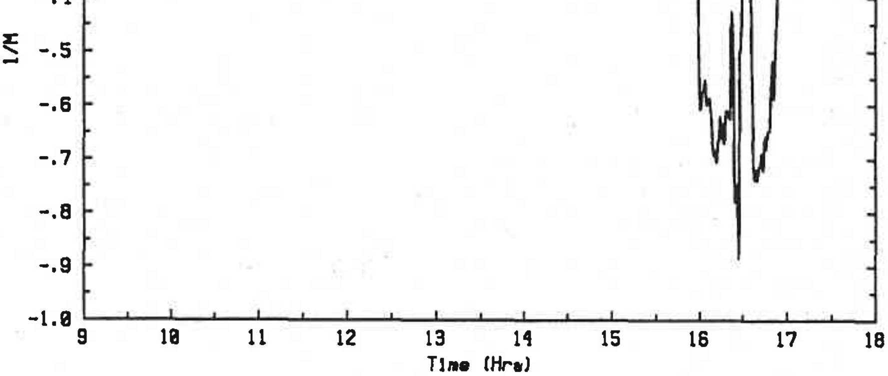

Figure 9: Inverse Monin-Obukhov length $(1/L)$ on 19 August 1986

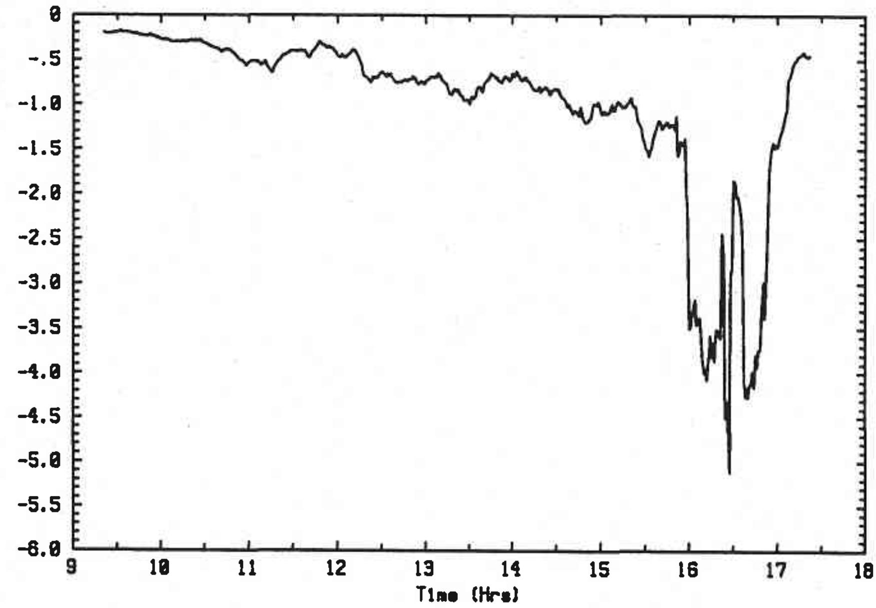

Figure 10: Richardson number (RI) on 19 August 1986

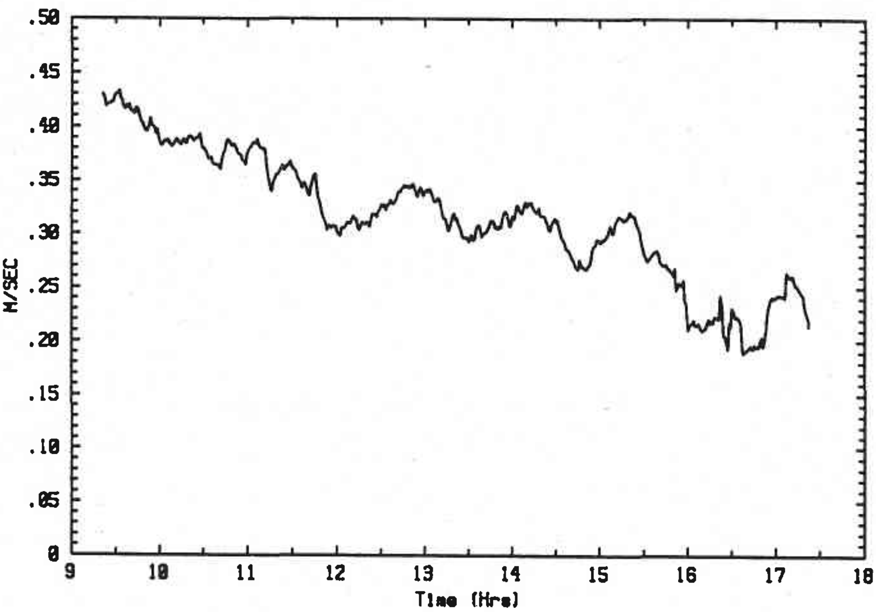

Figure 11: Friction velocity (U_*) on 19 August 1986

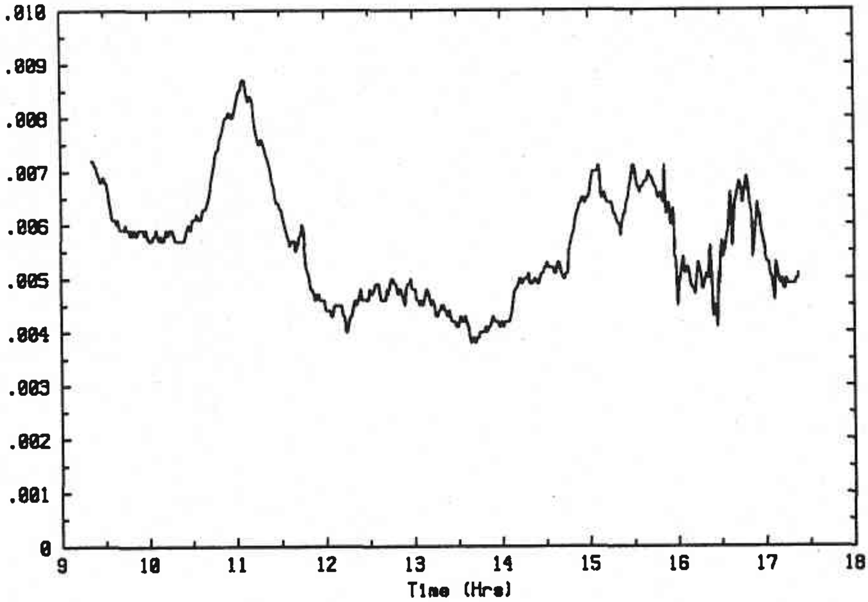

Figure 12: Drag coefficient $(C_{D,Z})$ on 19 August 1986

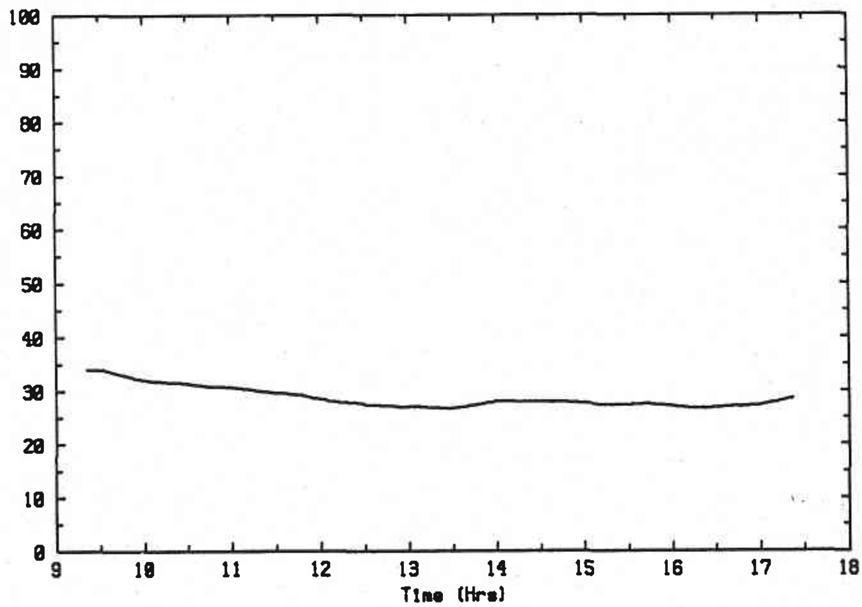

Figure 13: Relative humidity (RH) on 19 August 1986

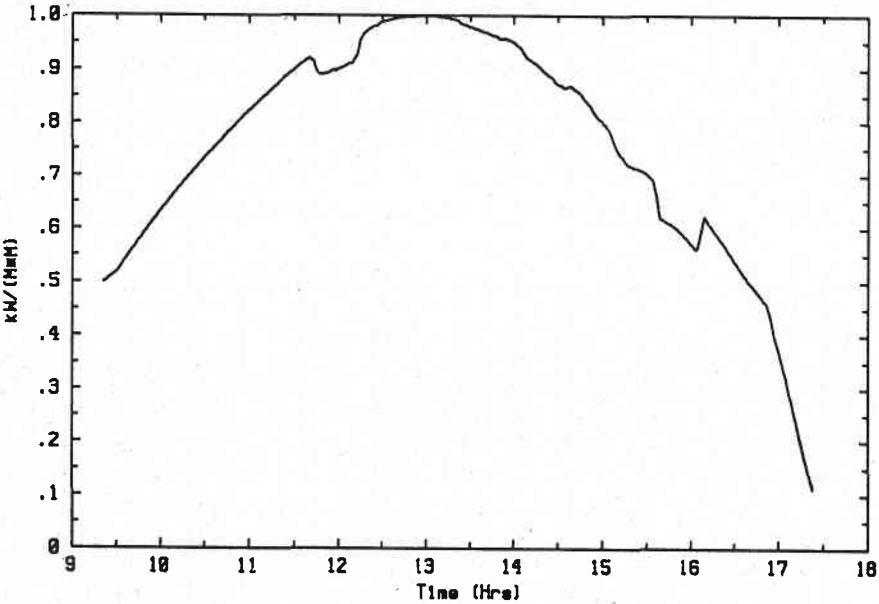

Figure 14: Insolation (I) on 19 August 1986

11 Comparison with other calculations

We can compare the results obtained so far with other methods of calculating the wind at various heights. Albini and Baughman (1979) use a simple logarithmic profile to extrapolate wind speeds. The comparison between predicted and observed wind speeds using the logarithmic profile is given in Table 3. These results show persistent under-prediction of the 2 m wind speed, and somewhat lower skill values.

In the preliminary report on the Annaburroo experiments (Cheney et al. 1987), a formula was derived from regression of the 2 and 10 m winds at the Clarke mast :

$$U_2 = 0.8329 + 0.57055U_{10} \tag{20}$$

While this formula gives good agreement between observed and predicted wind speed at 2 m over the whole data set, with $r^2 = 0.78$, it cannot be used to predict at different heights, thus negating its use for mid-flame wind speeds unless the mid-flame height is 2 m. Most of the time, the mid-flame height was around 1 m.

The default option for calculation of the wind speed in the U.S.A. fire- spread model is given in Rothermel (1983, p.33 and p.138). The ratio of mid-flame wind speed to 20 ft (6 m) wind speed is 0.4 for fuel type 3 (1 m high grasses). We extrapolate a logarithmic profile to 10 m, using $d = 0.75\,\mathrm{m}$ and $z_0 = 0.07\,\mathrm{m}$, to obtain a constant of 0.35, for the 2 m to 10 m wind-speed ratio, taking the mid-flame height as 2 m. Table 4 gives the comparison data as before. Again there is persistent under-prediction of the 2 m wind speeds by about 50%, with reduced skill scores.

Using values of $1/L = -0.15\,\mathrm{m}^{-1}$ and $C_{D,Z} = 0.005$, we obtain the results

Table 1: Predicted vs. Observed wind speeds at the Clarke mast 2 m anemometer. (ZPD from Metsite)

Date	No. of readings	ZPD (m)	<U> - U ($m\ s^{-1}$)		[<U> - U]/U (%)		Skill
			mean	σ	mean	σ	
04 Aug	413	0.05	-0.044	0.325	-1.1	8.0	0.994
05 Aug	366	0.05	0.780	0.349	24.0	11.6	0.938
06 Aug	383	0.05	0.106	0.371	2.5	12.9	0.987
14 Aug	602	0.05	0.300	0.568	12.7	56.4	0.895
15 Aug	484	0.05	0.144	0.362	7.1	13.0	0.973
16 Aug	494	0.05	0.166	0.195	6.6	8.1	0.992
17 Aug	400	0.05	0.171	0.204	4.4	5.3	0.996
18 Aug	380	0.05	0.087	0.262	2.9	8.4	0.994
19 Aug	483	0.05	0.473	0.243	16.1	9.0	0.971
20 Aug	454	0.05	0.454	0.348	12.9	27.0	0.979
21 Aug	450	0.05	0.325	0.246	8.5	6.2	0.989

Table 2: Predicted vs. Observed wind speeds at the Clarke mast 2 m anemometer. (ZPD at field location)

Date	No. of readings	ZPD (m)	<U> - U ($m\ s^{-1}$)		[<U> - U]/U (%)		Skill
			mean	σ	mean	σ	
04 Aug	413	0.70	-0.402	0.322	-9.6	7.9	0.985
05 Aug	366	0.70	0.447	0.312	14.1	10.8	0.975
06 Aug	383	0.55	-0.081	0.344	-3.0	12.0	0.989
14 Aug	602	0.45	0.258	0.561	10.3	56.0	0.903
15 Aug	484	0.55	0.062	0.349	3.4	12.6	0.978
16 Aug	494	0.70	0.016	0.212	1.2	8.5	0.994
17 Aug	400	0.70	-0.097	0.191	-2.5	5.0	0.997
18 Aug	380	0.60	-0.088	0.257	-2.1	8.2	0.994
19 Aug	483	0.45	0.372	0.238	12.9	9.1	0.980
20 Aug	454	0.40	0.344	0.336	10.0	26.3	0.985
21 Aug	450	0.55	0.164	0.226	4.1	6.0	0.995

Table 3: Predicted vs. Observed wind speeds at the Clarke mast 2 m anemometer. (Logarithmic profile)

Date	No. of readings	ZPD (m)	<U> - U ($m\ s^{-1}$)		[<U> - U]/U (%)		Skill
			mean	σ	mean	σ	
04 Aug	413	0.70	-1.006	0.310	-24.1	6.9	0.939
05 Aug	366	0.70	-0.221	0.290	-6.4	8.9	0.989
06 Aug	383	0.55	-0.710	0.320	-22.6	11.4	0.947
14 Aug	602	0.45	-0.094	0.310	-2.9	20.4	0.973
15 Aug	484	0.55	-0.500	0.320	-22.6	9.8	0.938
16 Aug	494	0.70	-0.436	0.235	-15.5	7.4	0.969
17 Aug	400	0.70	-0.735	0.215	-18.8	4.8	0.963
18 Aug	380	0.60	-0.669	0.258	-19.7	6.7	0.958
19 Aug	483	0.45	-0.240	0.221	-7.8	7.9	0.989
20 Aug	454	0.40	-0.245	0.299	-5.5	21.6	0.991
21 Aug	450	0.55	-0.484	0.211	-13.5	6.7	0.981

Table 4: Predicted vs. Observed wind speeds at the Clarke mast 2 m anemometer. (After Rothermel (1983))

Date	No. of readings	ZPD (m)	<U> - U ($m\ s^{-1}$)		[<U> - U]/U (%)		Skill
			mean	σ	mean	σ	
04 Aug	413	0.70	-2.256	0.388	-53.8	3.3	0.710
05 Aug	366	0.70	-1.461	0.343	-43.3	5.2	0.808
06 Aug	383	0.55	-1.764	0.427	-53.9	6.2	0.714
14 Aug	602	0.45	-0.964	0.447	-51.0	8.3	0.712
15 Aug	484	0.55	-1.253	0.501	-55.9	5.4	0.679
16 Aug	494	0.70	-1.520	0.387	-55.6	3.0	0.688
17 Aug	400	0.70	-2.133	0.360	-54.4	2.4	0.703
18 Aug	380	0.60	-1.902	0.467	-55.8	3.6	0.688
19 Aug	483	0.45	-1.571	0.436	-51.8	3.4	0.731
20 Aug	454	0.40	-2.058	0.533	-52.6	11.6	0.715
21 Aug	450	0.55	-2.026	0.458	-54.2	2.6	0.706

Table 5: Predicted vs. Observed wind speeds at the Clarke mast 2 m anemometer. ($1/L$ = -0.15 m^{-1} and $C_{D,Z} = 0.005$)

Date	No. of readings	ZPD (m)	<U> - U ($m\ s^{-1}$)		[<U> - U]/U (%)		Skill
			mean	σ	mean	σ	
04 Aug	413	0.70	1.335	0.452	31.7	9.4	0.890
05 Aug	366	0.70	2.041	0.601	61.4	14.6	0.614
06 Aug	383	0.55	1.069	0.614	31.1	17.8	0.868
14 Aug	602	0.45	0.650	0.342	38.9	23.4	0.863
15 Aug	484	0.55	0.541	0.466	25.0	15.3	0.910
16 Aug	494	0.70	0.706	0.247	26.1	8.5	0.929
17 Aug	400	0.70	1.164	0.309	29.8	6.7	0.908
18 Aug	380	0.60	0.883	0.407	25.9	10.1	0.923
19 Aug	483	0.45	1.126	0.392	37.2	9.7	0.856
20 Aug	454	0.40	1.305	0.481	35.1	32.6	0.878
21 Aug	450	0.55	1.140	0.389	30.3	7.3	0.901

Table 6: Predicted vs. Observed wind speeds at the Clarke mast 2 m anemometer. ($1/L = -15U_{10}^{-3}$)

Date	No. of readings	ZPD (m)	<U> - U ($m\ s^{-1}$)		[<U> - U]/U (%)		Skill
			mean	σ	mean	σ	
04 Aug	413	0.70	-1.093	0.422	-27.5	13.2	0.924
05 Aug	366	0.70	-0.638	0.580	-20.7	21.3	0.937
06 Aug	383	0.55	-0.579	0.348	-18.6	12.6	0.960
14 Aug	602	0.45	0.152	0.290	7.9	20.8	0.973
15 Aug	484	0.55	-0.021	0.403	-2.3	14.8	0.971
16 Aug	494	0.70	0.021	0.256	-0.1	10.4	0.992
17 Aug	400	0.70	-0.500	0.265	-13.3	7.8	0.980
18 Aug	380	0.60	-0.220	0.323	-7.9	11.0	0.988
19 Aug	483	0.45	0.178	0.335	4.2	13.0	0.985
20 Aug	454	0.40	0.024	0.395	-1.2	11.7	0.990
21 Aug	450	0.55	-0.134	0.332	-4.5	9.9	0.991

shown in Table 5. These values are typical of daytime conditions. This shows consistent over-prediction of the measured wind, with only fair skill scores.

We have used the data from this experiment to produce a heuristic formula that will predict the stability from simple meteorological measurements. In the unstable case with strong insolation,

$$\frac{1}{L} = -15U_{10}^{-3} \tag{21}$$

where L is in metres and U_{10} is in m s^{-1}. Though Equation 21 is strictly valid only for constant temperature, sensible heat flux and drag coefficient (as may be found from examination of Equation 25 in Appendix A), it was found to be generally useful. The results of Table 6 show good agreement with the observed values and high skill scores.

12 Mid-flame wind speeds

With confidence in the method of predicting winds at different heights, we can calculate the mid-flame and 10 m wind speed at the fire anemometers. These are then used for input to the Rothermel and MacArthur models respectively. Information on fuel height is used to calculate the zero-plane displacement for each fire, and the mid-flame height is calculated from the flame height data estimated by the fire behaviour observers. The local friction velocity is calculated from the drag coefficient and the wind speed at 2 m. The Clarke mast mid-flame wind speed is also calculated, using both the 2 m and 10 m wind speeds as inputs to the wind profile model. Most calculations produce very similar results for either input, but occasionally the difference is about 1 m s^{-1}, probably the result of statistical variability. A sample calculation is given in Table 7. In this calculation, the flame height is 1 m and the fuel height 0.1 m.

13 Discussion

The utility of the heuristic relationship of Equation 21 is surprising. Similarity theory, as outlined in Appendix A, gives the formula for the Monin-Obukhov length as Equation 25. The drag coefficient, $C_{D,Z}$, is site specific and varies during the course of the day as do T, the temperature, and H, the sensible heat flux. Thus the value of -15 in Equation 21 can hardly be expected to be a constant. Nevertheless, the heuristic formula appears to be surprisingly robust when tested on daytime data from the Wangara experiment.

Table 8 lists the data from Station 5 during Day 31 of the Wangara experiment (Clarke et al., 1971). There were no 10 m wind data, so the 8 m wind data (U_8) were used to predict the 2 m wind data (U_2) assuming a logarithmic profile (Method 1), a constant $1/L = -0.15$ m^{-1} (Method 2), as in Table 5, and Equation 21 as in Table 6 (Method 3). The roughness length for this station is given as 1.2 mm (ibid.). We again find that the logarithmic profile, which is equivalent to $1/L = 0$, under-predicts, a constant value of $1/L = -0.15$ m^{-1} over-predicts, whereas Equation 21 produces very good estimates of the 2 m wind.

Table 7: Sample Calculation of Mid-Flame and 10 Metre Wind Speeds at Fire Anemometers and Clarke Mast

Anemometer	Wind Speed m s^{-1}			
	2 m	Mid-flame	10 m	
Clarke Mast	4.55†	2.93		§
Clarke Mast		2.97	6.14†	§
1	4.50†	2.68	6.08	#
2	5.45†	3.25	7.36	#
3	5.76†	3.43	7.78	#
4	6.07†	3.62	8.20	#

† Inputs to the profile models.
§ Mid-flame wind-speed prediction from both 2 m and 10 m inputs.
# Mid-flame and 10 m wind-speed predictions using the 2 m fire anemometers.

Table 8: Predicted and Observed 2 m wind speeds (m s^{-1}) from Station 5, Day 31,Wangara Experiment

Time	U_8	U_2	U_2 (predicted)		
	(observed)		Method 1	Method 2	Method 3
			$(1/L=0)$	$(1/L=-0.15\,m^{-1})$	$(1/L=-15U_8^{-3})$
0900	6.31	5.54	5.32	5.70	5.60
0100	7.35	6.48	6.19	6.64	6.48
1100	7.01	6.17	5.91	6.33	6.19
1200	6.61	5.86	5.57	5.97	5.86
1300	5.88	5.24	4.95	5.31	5.24
1400	5.81	5.17	4.90	5.25	5.18
1500	5.62	4.99	4.74	5.07	5.03
1600	6.89	5.99	5.81	6.23	6.09
1700	6.35	5.47	5.35	5.74	5.64
$\Sigma(<U>-U)^2$			0.55	0.24	0.04

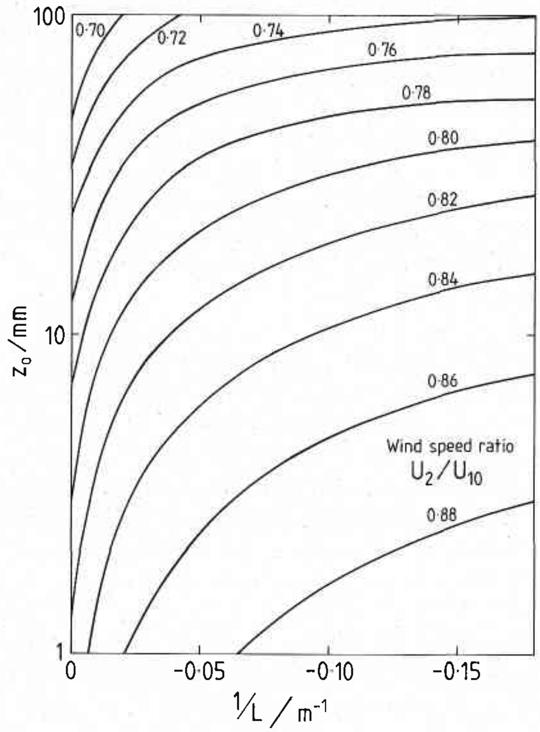

Figure 15: Wind speed ratios as a function of roughness and Monin-Obukhov lengths

Figure 15 plots the theoretically expected ratio between mean wind speeds at heights of 2 m and 10 m as a function of z_0 and $1/L$. This ratio changes rapidly near neutral conditions ($1/L = 0$) for constant roughness length, but varies more slowly as the magnitude of $1/L$ increases. However, the ratio does indeed vary with $1/L$, and it is for this reason that improved wind predictions can be made by incorporating $1/L$. It may be noted, however, that for a constant z_0 - say of 0.001 m - similar wind predictions will be obtained for $1/L$ ranging between -0.02 m^{-1} and - 0.06 m^{-1}, a factor of three. This rather suggests that the value of -15 in the heuristic formula is not critical, and reasonable mean wind speed ratios may be obtained, even if the estimation of $1/L$ is out by a factor of two, and possibly even a factor of three.

14 Conclusions

Meteorological data collected during the Northern Territory Grasslands Fire Experiment were required to obtain wind predictions as inputs to the models of fire spread that were being tested. The fire-spread models are, in general, sensitive to the input value of the wind speed. The Rothermel model of fire spread requires wind at mid-flame height whereas standard wind observations in Australia are taken at 10 m height. Six methods of downward extrapolation have been examined and tested against an independent set of wind data collected at 2 m and 10 m heights.

The simplest method, used as the default in the Rothermel fire-spread model, is to assume that U_2 is proportional to U_{10} with a ratio of 0.35. The skill score of such a procedure is about 0.7 and it regularly underestimates the observed 2 m wind speed by about 1.5 m s^{-1}. If a simple logarithmic wind profile is used then skill scores rise to approximately 0.95 but the model continues to underestimate the wind by about 0.5 m s^{-1}, on average. Incorporating atmospheric stability through the Monin-Obukhov length calculated from the wind and temperature at two heights raises the skill scores to about 0.97 to 0.99 and, on average, over-predicts the winds by 0.1 m s^{-1}. Using a single wind speed and the heuristic formula, $1/L = -15U_{10}^{-3}$, to estimate the stability also produces good skill scores and under-predicts the wind speed by about 0.2 m s^{-1}. Using a single, representative, value for the Monin-Obukhov length and the drag coefficient produces rather poorer predictions and skill scores.

These results indicate that inclusion of atmospheric stability parameters can be used to improve wind predictions, but it remains uncertain whether such refinement in wind speed is worthwhile, given the uncertainties inherent in the model, and the major instrumental effort required to obtain information on the Monin-Obukhov length, L.

Estimation of L requires information on the wind speed and atmospheric vertical temperature structure obtained from a minimum of two levels, though three levels is to be preferred. An assumption regarding the Richardson number dependence of Z/L is also needed. However, the results herein indicate that simple empirical relations that link L and U, the wind speed, can provide improved wind predictions for a substantially reduced instrumental effort.

Appendix A - Profile calculations

The forms of ϕ_M and ϕ_H are different for the stable and unstable case. For the unstable case, $\Delta\theta < 0$, we use the Businger-Dyer forms (Businger, 1988),

$$\phi_M = \left(1 - \alpha_1 \frac{Z}{L}\right)^{-\frac{1}{4}} \tag{22}$$

$$\phi_H = \left(1 - \alpha_2 \frac{Z}{L}\right)^{-\frac{1}{2}} \tag{23}$$

For the stable case, we follow Webb (1970) and use

$$\phi_M, \phi_H = 1 + \alpha_3 \frac{Z}{L} \tag{24}$$

with $\alpha_3 = 5$. Different authors advocate various possible choices for α_1 and α_2 (and for k, von Karman's constant). We follow Bergstrom (1986) and use $\alpha_1 = 22$ and $\alpha_2 = 13$. The variable L is the Monin-Obukhov length and is defined in terms of the heat flux, H, by

$$L = \frac{\rho\, C_p\, T\, (C_{D,Z})^{1.5}}{k\, g\, H\, U_*^{-3}} \tag{25}$$

where ρ, C_p and T are the density, isobaric specific heat and absolute temperature of the air and g is the gravitational acceleration.

The usual micro-meteorological practice (Paulson, 1970) is to express the integrated form of the similarity theory profiles in terms of their departure from neutral stability as

$$U(Z, U_*, \theta_*) = \frac{U_*}{k}\left[\ln\left(\frac{Z}{z_0}\right) - \psi_1\left(\frac{Z}{L}\right)\right] \tag{26}$$

$$\theta(Z, U_*, \theta_*) - \theta_0 = \frac{\theta_*}{k}\left[\ln\left(\frac{Z}{z_0}\right) - \psi_2\left(\frac{Z}{L}\right)\right] \tag{27}$$

where, for $L < 0$

$$\psi_1 = 2\ln\left(\frac{1+x}{2}\right) + \ln\left(\frac{1+x^2}{2}\right) - 2\arctan x + \frac{\pi}{2} \tag{28}$$

$$x = \left(1 - \alpha_1 \frac{Z}{L}\right)^{\frac{1}{4}} \tag{29}$$

$$\psi_2 = 2\ln\left(\frac{1+y}{2}\right) \tag{30}$$

$$y = \left(1 - \alpha_2 \frac{Z}{L}\right)^{\frac{1}{2}} \tag{31}$$

and for $L > 0$

$$\psi_1 = -\alpha_3 \frac{Z}{L} \tag{32}$$

$$\psi_2 = \psi_1 \tag{33}$$

Equations 26 and 27 are based on integrating the wind and temperature profiles from a height z_0 at which $U(z_0) = 0$ and $\theta(z_0) = \theta_0$, respectively. However, to obtain Equation 28, Paulson (1970) replaced z_0 by zero. (Nickerson and Smiley, 1975; Benoit, 1977). Our interest, as evident in Equations 15 and 16 for ΔU and $\Delta\theta$, concerns the integration between two arbitrary heights. Though this can be accomplished by substituting in Equations 26 and 27 and subtracting, an alternative approach is to directly integrate Equations 15 and 16 to produce

$$\Delta U = \frac{U_* \Omega_M}{k} \tag{34}$$

$$\Delta\theta = \frac{\theta_* \Omega_H}{k} \tag{35}$$

where, in the unstable case,

$$\Omega_M = \int_{Z_1}^{Z_2} \frac{\phi_M}{Z} dZ = \left| \ln\left(\frac{x-1}{x+1}\right) + 2\arctan(x) \right|_{X_1}^{X_2} \tag{36}$$

$$\Omega_H = \int_{Z_1}^{Z_2} \frac{\phi_H}{Z} dZ = \left| \ln\left(\frac{y-1}{y+1}\right) \right|_{Y_1}^{Y_2} \tag{37}$$

where x and y are as above, and X_1, X_2, Y_1 and Y_2 are the transforms of Z_1 and Z_2 by Equations 29 and 31.

The Monin-Obukhov length can be obtained from ΔU and $\Delta\theta$. Using the alternative definition for L in terms of θ_*,

$$\theta_* = \frac{H}{\rho C_p U_*} \tag{38}$$

we obtain

$$\frac{1}{L} = \frac{k\, g\, \theta_*}{T\, U_*^2} = \frac{g}{T} \frac{\Delta\theta}{(\Delta U)^2} \frac{\Omega_M^2}{\Omega_H} \tag{39}$$

so that it is possible to solve iteratively to find L.

The Monin-Obukhov length L and Richardson number RI are related by

$$RI = \frac{g}{\theta} \frac{\left(\frac{\partial\theta}{\partial z}\right)}{\left(\frac{\partial U}{\partial z}\right)^2} = \frac{g}{\theta} \frac{\theta_*}{\left(\frac{U_*}{kZ}\right)^2} \frac{\Omega_H}{\Omega_M^2} = \frac{Z\Omega_H}{L\Omega_M^2} \tag{40}$$

Webb (1970) recommends that derivatives be calculated as

$$\Delta\theta' = \frac{\Delta\theta}{\sqrt{Z_1 Z_2}} \ln\left(\frac{Z_2}{Z_1}\right) \tag{41}$$

where

$$\Delta\theta = T_2 - T_1 + \Gamma(Z_2 - Z_1) \tag{42}$$

$$\Gamma = 0.0098 \mathrm{K\,m^{-1}} \tag{43}$$

Appendix B - Metsite data

Accompanying this report is a floppy disk which contains computer files of the Metsite data. The format of the disks is IBM-PC compatible, MS-DOS, 360 kbyte size. The data files are named MSNTxxxx.DAT, where "xxxx" is the date in the form MMDD, e.g. the file of data for the 4th of August 1986 is named MSNT0804.DAT. The data within the files are laid out as in Table 9. Because the aim of the experiment was to test the various models of fire spread, mid-flame and 10 m wind speeds were calculated on the basis of the fire anemometers. This report, however, deals with data from the Clarke mast and Metsite. Thus the data disk contains only these data.

Table 9: Data layout on Metsite data files

Data Item #	Contents
1	Line number
2	Hour
3	Minute
4	Clarke mast wind speed in m s^{-1} at 2 m
5	Clarke mast wind speed in m s^{-1} at 10 m
6	Metsite wind speed in m s^{-1} at 2 m
7	Metsite wind speed in m s^{-1} at 10 m
8	Metsite wind direction in degrees at 10 m
9	Metsite temperature in °C at 2 m
10	Metsite temperature in °C at 10 m
11	Relative humidity in %
12	Insolation in kW m^{-2}

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