MODELLING SURFACE AIRFLOW FOR FOREST AND RURAL FIRE DANGER RATING: COMPARISONS BETWEEN ACTUAL OBSERVATIONS AND PREDICTED VALUES

J. R. MOORE, L. G. FOGARTY

New Zealand Forest Research Institute,
Private Bag 3020, Rotorua, New Zealand

J. C. SUÁREZ and B. A. GARDINER

Forestry Commission Research Agency, Northern Research Station,
Roslin, Midlothian, EH25 9SY, Scotland.

(Received for publication 6 May 1997; revision 28 May 1998)

ABSTRACT

The performance of three airflow models (Flowstar, MSFD-PC, and MS-Micro/3) was compared as a means of providing wind speed and wind direction data for use in the assessment of forest and rural fire danger. At Cowal Peninsula, Scotland, and the Manawatu Gorge, New Zealand, six simulations were performed with each model, using data for incident winds from the westerly quarter and incorporating effects of complex terrain. Model performance was similar for both study areas. The mean wind speed prediction error for the best-performing model (MS-Micro/3) was approximately 30%. Without simulation, prediction errors for average wind speed were 67% at Cowal Peninsula and 50% at Manawatu Gorge. Root mean square errors for wind direction prediction by models averaged 86° at Cowal Peninsula and 26° at Manawatu Gorge. With the exception of MS-Micro/3 output for the Manawatu Gorge area, wind direction simulations at both sites produced unacceptable results.

Three independent data sets were used to examine the influence of wind speed prediction errors on fire danger rating assessment. Error magnitudes associated with use of airflow modelling of single point source data altered the number of days allocated to Very High and Extreme fire danger classes, differences being much greater for areas with a severe fire climate. The Jackson-Hunt linear microscale models tested can provide wind speed information which will improve the accuracy of fire danger rating.

Keywords: wind; airflow modelling; fire danger rating.

INTRODUCTION

Behaviour of forest and rural fires is strongly affected by weather factors. The effects of individual and combined weather factors (temperature, wind speed and direction, relative humidity, and rainfall) and their interaction with other components of the fire environment (i.e., fuel and topography—Countryman 1972) can be complex and difficult to interpret.

Systematic evaluation and integration of factors influencing fire behaviour can be achieved by a process known as fire danger rating (Stocks *et al.* 1989).

Outputs from the New Zealand Fire Danger Rating System (NZFDRS) include Fire Weather Index (FWI) System codes and indices (Van Wagner 1987), which are standard numerical ratings of fuel dryness, the ease of fire spread, and difficulty of control. The FWI values are combined with information about fuel and topography to provide estimates of fire behaviour (e.g., rate of headfire spread, rate of fireline perimeter growth, and fireline intensity). The estimates are used to support fire management decisions about prevention, pre-suppression, and operational suppression. They can be adapted to a range of requirements. For example, fire prevention campaigns to raise public awareness in areas where extreme fire danger conditions are expected can be mounted at national, regional, and district levels through television, radio, and print media. Individual land managers to whom burning permits have been issued can be contacted personally. In New Zealand, weather data for fire danger rating are obtained from a number of manual and remote automatic weather stations. Outputs provide an accurate estimate of fire danger only in the zone immediately surrounding each station. They offer no more than an indication of fire danger conditions outside this zone.

The usefulness of NZFDRS output can be extended by aggregating and displaying the fire danger condition over large areas (Latham 1993). Interpolation techniques can be used, for which the following methods have been listed by Lee & Anderson (1989):

- The Nearest Neighbour technique assumes that a value at a given point is the same as that recorded at the nearest weather station.
- The Cell Assignment method applies weather station data to areas of similar topography and climate.
- The Weighting of Moving Averages technique uses data from a number of weather stations. These are weighted according to distance from the point of interest and an average value is derived.

The Nearest Neighbour technique can provide immediate results, but ignores the effects of differential topography and climate and is thus unlikely to perform well in areas of complex terrain. Although Cell Assignment deals with some differential effects, gradients are ignored and zone definition is difficult. Weighting of Moving Averages provides isopleths (smooth gradients) between recording sites but may ignore potentially important features (e.g., valley winds, dominant terrain features) if these sites are widely spaced or located in different catchments (Lee & Anderson 1989). Further difficulties may arise because most fire danger rating systems are based on non-linear relationships and distortions arise from the input of averaged weather data (Latham 1993).

Alternatively, the weather inputs to the equations for fire danger rating can be interpolated or estimated using models based on fundamental physical relationships. A number of models are available ranging from simple analogue techniques through to three-dimensional mesoscale models. Mesoscale meteorological models include the effects of topography and climate. This is particularly important in New Zealand where conditions are often variable over short distances. These models depend on the existence of extensive meteorological networks and require large amounts of computer time. Maintenance and use are both expensive (Physick 1985; Hayes & Ferguson in prep.). Reduction of mechanical and thermodynamic relationships to simplified linear equations may offer the most practical method for assessing fire danger in complex terrain (Fosberg *et al.* 1976).

Wind is the most dynamic meteorological force affecting fire behaviour (Cheney 1981). Wind speed influences the rate at which fine fuel dries (Van Wagner 1987) and the rate at which fire spreads. It affects flame angle and convection and consequently the preheating of fuels ahead of the fire front (Cheney 1981). Wind direction influences fire spread. Wind has a direct impact on other meteorological factors and is strongly influenced by local terrain. Wind and slope factors may interact, producing either positive or negative effects on fire behaviour. The modelling of wind speed and direction is therefore a fundamental component of all fire danger rating systems.

Linear microscale models can be used to predict the effects of topography on wind speed from simplified equations of motion. Although the use of approximations confines the applicability of models to a more specific set of conditions (Inglis *et al.* 1995), studies by Barnard (1991) and Walmsley *et al.* (1990) demonstrated good agreement with actual observations in simple terrain (neutrally stable flow over isolated or two-dimensional hills with no flow separation).

In this study, three linear microscale airflow models were examined for effectiveness in providing data for the assessment of fire danger rating in areas of complex terrain.

METHOD

Selected models, all based on linear theory for two-dimensional turbulent flow over low hills (Jackson & Hunt 1975) were :

- **Flowstar**, developed by Cambridge Environmental Research Consultants, England, and described by Hunt *et al.* (1988a,b);
- **MS-Micro/3**, developed by the Atmospheric Environment Service, Canada, and described by Walmsley *et al.* (1986);
- **MSFD-PC**, also developed by the Atmospheric Environment Service, Canada, and described by Beljaars *et al.* (1987).

Wind speeds and directions predicted by each model were compared with those observed in two areas of complex terrain. Average prediction error was assessed in terms of its effect on fire danger rating.

Theoretical Background

In all three models the atmosphere close to the ground is divided into two regions (Fig. 1). The outer region has no viscosity and airflow is irrotational. The air in this region is therefore incompressible and the flow is pressure-driven. The inner region is bounded by the land surface, and disturbances to airflow are assumed to be caused entirely by variation in terrain at this boundary. In both regions a constant advection velocity is assumed (Beljaars *et al.* 1987).

Models based on Jackson-Hunt theory are designed to conserve mass while solving momentum (Navier-Stokes) equations (Barnard 1991). Because of difficulties in determining an exact solution to the momentum equation in complex terrain, two approximations are

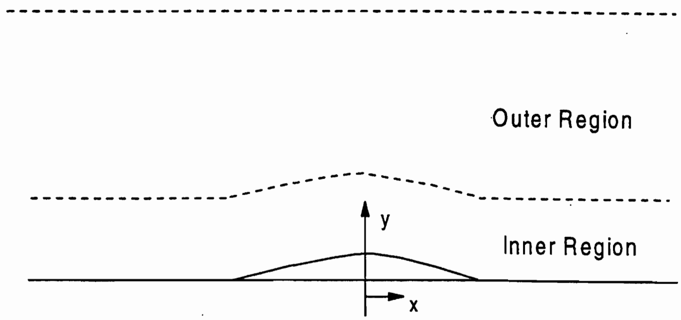


FIG. 1–Flow regimes for two-dimensional turbulent flow over a low hill (after Jackson & Hunt 1975).

used. Firstly, physical flow relationships are simplified by use of a mixing-length closure scheme for the turbulent processes. Secondly, momentum equations are linearised and solved by perturbation techniques. These introduce a constant flow field to a flat, homogeneous plane. A logarithmic profile is assumed, and a low hill of limited horizontal and vertical extent is introduced. The resulting small perturbations are calculated and added to the (vertically displaced) logarithmic profile to achieve the final solution. The perturbations are assumed to vanish at the boundary of the modelling domain where the flow is assumed to be unaffected by the hill and identical to the logarithmic profile (Barnard 1991; Teunissen *et al.* 1987). The Jackson-Hunt theory was extended into three dimensions by Mason & Sykes (1979).

Model characteristics

Flowstar takes account of different types of stratification. In this it differs from the MS-Micro/3 and MSFD-PC models, which consider neutral stratification only. Stratification options currently available in Flowstar are indicated in Fig. 2. Maximum resolution levels for terrain and surface roughness information are lower than those required for MS-Micro/3.

MS-Micro/3 is a microcomputer version of the numerical model MS3DJH/3R (Walmsley *et al.* 1986). It uses Fast Fourier Transforms (FFTs) to calculate velocity and pressure perturbations, and converts values back into real space mode using inverse FFTs (Walmsley *et al.* 1993). This procedure imposes limitations relating to the size of the modelling domain and the maximum steepness of terrain slopes. Grids (information units) for terrain and surface roughness are squares of up to 256 × 256 points. Requirements for computer memory are low and processing time is shorter than for finite element or finite difference models (Walmsley *et al.* 1990). Major limitations of MS3DJH models are the approximation of the advection terms and, especially, the level of closure (Beljaars *et al.* 1987). Equilibrium between production and dissipation of turbulent energy, necessary for mixing-length closure, is seldom determined where there is changing surface roughness. Topographic perturbations also produce non-equilibrium effects which are incompatible with mixing-length closure.

The MSFD-PC (Mixed Spectral Finite Difference) model incorporates higher order closure schemes as alternatives to mixing-length closure. Equations of motion around an

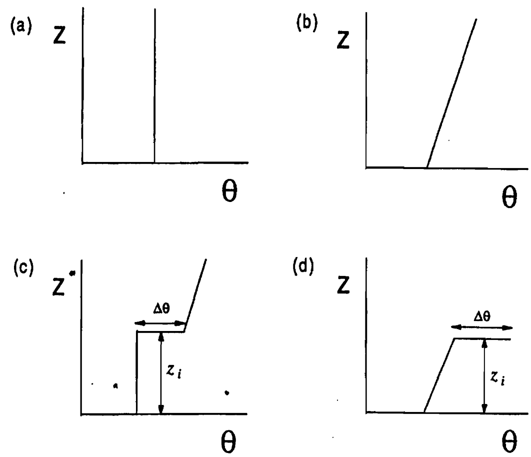


FIG. 2–Graphical representation of the upstream stratification options available in Flowstar. (a) neutral stratification; (b) constant stable stratification; (c) neutral layer capped by an inversion of potential temperature step Δθ with a slightly stable layer above that; (d) stable layer beneath a strong inversion (after Inglis *et al.* 1995). z is the height above the ground and θ is the potential temperature.

upstream or other unperturbed profile are linearised and transformed, using FFTs, into two horizontal co-ordinates. The resulting set of ordinary differential equations in the vertical co-ordinate is solved by means of a finite difference technique (Beljaars *et al.* 1987). Information units are square grids of up to 128 × 128 points. Computation time is much shorter than for a three-dimensional finite difference model, but about 20 times greater than for MS-Micro/3 (Beljaars *et al.* 1987).

Experimental Sites

Two areas were selected for this study: Cowal Peninsula in Scotland, located 70 km north-west of Glasgow; and an area in the Tararua Range near the Manawatu Gorge, New Zealand, which lies 10 km south-east of Palmerston North. These areas were chosen for complexity of terrain which has not been addressed in previous studies (Walmsley *et al.* 1990; Barnard 1991).

Topography

The Cowal Peninsula study area (Fig. 3) has a maximum elevation of 741 m a.s.l. There are two valley systems—the main Glenshellish Valley running north–south, and Bernice Glen, orientated at 120°–300°. Wind direction is strongly influenced by the valley terrain (Hannah 1993). The majority of slopes are less than 14°, but slopes as steep as 40° are common. Flow separation in the lee of these steeper slopes was expected to result in significant prediction errors.

The topography of the Manawatu Gorge study area is shown in Fig. 4. The maximum elevation is 550 m a.s.l. Although numerous small watercourses drain the ridge, the topography is quite simple in comparison with that of most New Zealand mountain terrain

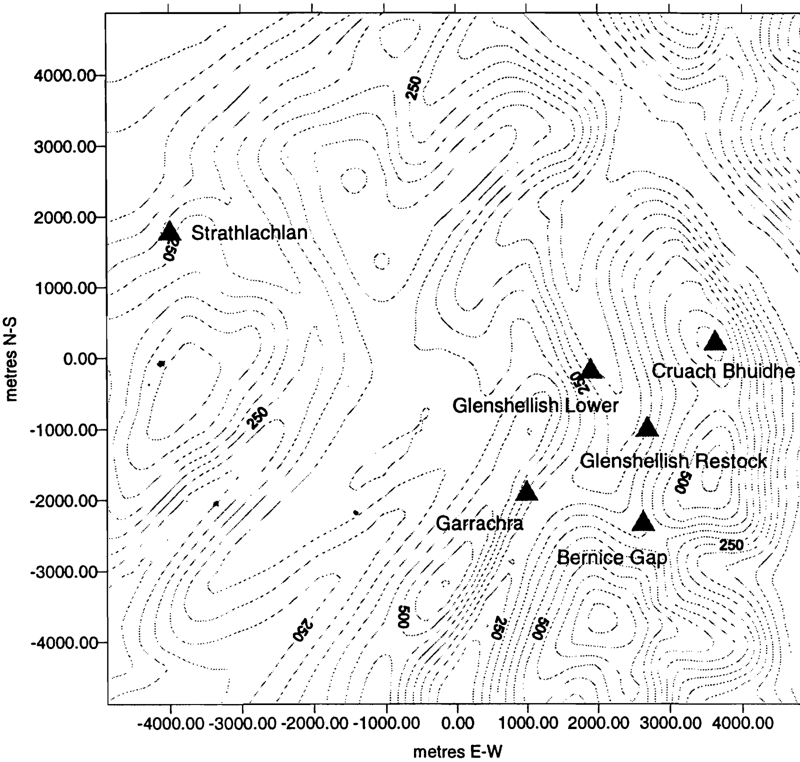


FIG. 3—Topography of the Cowal Peninsula study area. Contour interval is 50 m. Locations of meteorological stations are shown as triangles.

(Reid 1985). The angle of the majority (88%) of the slopes is less than 14° and linearisation errors in J-H models were expected to be small.

Vegetation

The Cowal Peninsula contains significant areas of coniferous forest, mainly Sitka spruce (*Picea sitchensis* (Bong.) Carr.) with some lodgepole pine (*Pinus contorta* Dougl.). Non-forested areas consist mainly of grassland and heather (*Calluna vulgaris* (L.) Hull).

In the Manawatu Gorge study area, flat land to the north-west and south-east of the ridge is covered mainly with improved and unimproved pasture (Newsome 1987). Vegetation on the ridge is a mixture of grassland, broadleaved forest, and scrub.

Wind Data Collection

In 1989, Vector cup anemometers and wind vanes were installed by the British Forestry Commission at six locations (Fig. 3). Wind data at a height of 10 m were monitored continuously with battery-powered Holtech loggers. Hourly averages between September 1990 and January 1992 were used for this study.

Manawatu Gorge data were collected by the New Zealand Meteorological Service (Reid 1985). Anemometers at five locations (Fig. 4) were operated concurrently during the period

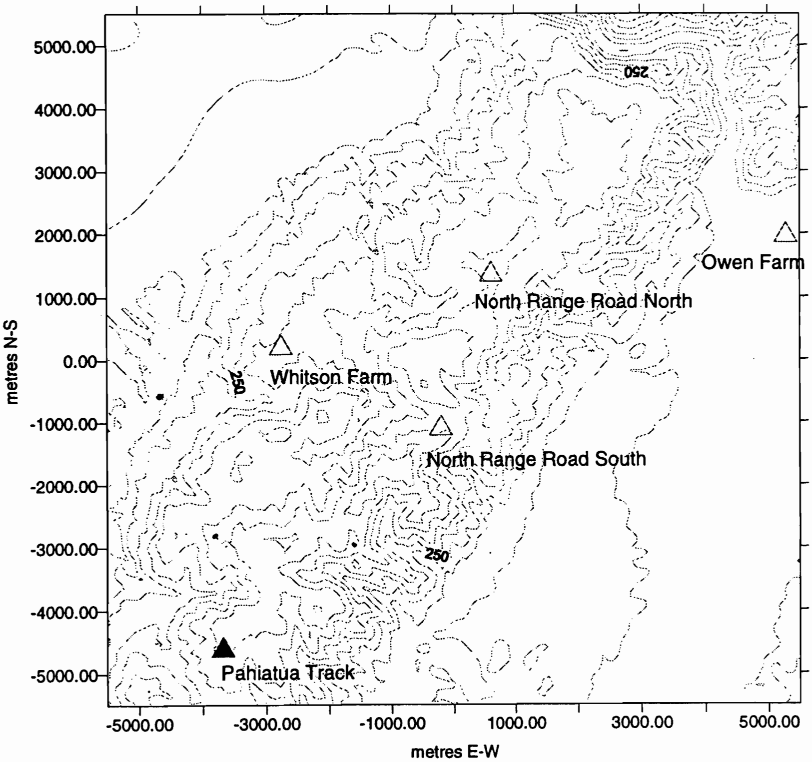


FIG. 4–Topography of the Manawatu study area. Contour interval is 50 m. Locations of meteorological stations are shown as triangles. Open triangles represent temporary Lambrecht anemometers; the solid triangle represents a permanent Munro anemometer.

January–March 1983. Wind data were also collected at a reference site (Palmerston North Airport) located approximately 10 km north-west of the study area. Hourly wind speed and wind direction data derived from Lambrecht anemometers were averages of values recorded over whole hours. For the Munro anemometer, the average of values recorded over the 10-min period before each nominated hour was used as the hourly value.

Data Preparation

Wind speed and direction

The study was confined to periods when all recording stations in each study area were operating concurrently. Records were also omitted if hourly wind speed was less than 2 m/s or the wind direction was identical for 3 consecutive hours.

The Strathlachan and Palmerston North stations were chosen as upwind reference sites, westerly airflows being prevalent in both study areas. Data from the other stations (recording sites) were sorted into groups based on wind direction. At each reference site, six 10° sectors between 250° and 300° were selected for comparison with results from the model simulations (Table 1). For each sector the average wind speed at the reference site and the average concurrent wind speed and direction for the recording sites were calculated.

TABLE 1--Actual data for six 10° wind direction sectors at (a) Cowal Peninsula and (b) Manawatu Gorge.

Station	**Sector 1**		**Sector 2**		**Sector 3**		**Sector 4**		**Sector 5**		**Sector 6**	
(a) Cowal Peninsula	**n=126**		**n=77**		**n=71**		**n=66**		**n=71**		**n=63**	
	Speed (m/s)	Direction (degrees)	Speed (m/s)	Direction (degrees)	Speed (m/s)	Direction (degrees)	Speed (m/s)	Direction (degrees)	Speed (m/s)	Direction (degrees)	Speed (m/s)	Direction (degrees)
Strathlachlan	9.5	250	9.2	260	8.8	270	11.8	280	11.3	290	8.8	300
Cruach Buidhe	15.7	237	15.0	237	15.4	274	20.2	255	19.6	253	15.4	274
Bernice Gap	8.0	269	7.9	277	12.5	268	11.3	242	13.5	271	12.5	268
Garrachra	6.6	215	5.7	213	3.0	102	3.8	164	3.1	143	3.0	102
Glenshellish Restock	3.5	260	3.6	275	4.7	322	5.2	296	4.9	308	4.7	322
Glenshellish Lower	3.9	103	3.5	94	6.3	160	4.8	39	5.4	56	6.3	160
(b) Manawatu Gorge	**n=18**		**n=21**		**n=54**		**n=42**		**n=38**		**n=22**	
	Speed (m/s)	Direction (degrees)	Speed (m/s)	Direction (degrees)	Speed (m/s)	Direction (degrees)	Speed (m/s)	Direction (degrees)	Speed (m/s)	Direction (degrees)	Speed (m/s)	Direction (degrees)
Palmerston North	4.6	250	5.4	260	7.4	270	8.7	280	8.8	290	6.6	300
Pahiatua Track	13.7	265	16.4	280	20.8	281	21.2	279	20.9	280	18.7	278
Whitson Farm	7.2	281	8.9	297	11.4	304	12.4	301	12.9	302	10.4	306
North Range Road N	9.9	282	10.0	295	12.7	304	13.6	304	12.9	305	10.6	303
North Range Road S	9.9	288	11.6	298	13.0	301	12.7	307	13.1	306	11.8	308
Owen Farm	5.4	274	6.4	281	9.1	293	9.4	292	8.3	302	9.2	299

Airflow models based on J-H theory assume that the cross-correlation coefficient between the reference site and each recording site is unity, i.e., that all sites are subject to the same overall weather pattern (Bowen & Mortensen 1996). Correlation coefficients (r) for the relationship between wind speed and direction at the reference site and at each recording site are given in Table 2. High correlation between data at the reference and recording sites is a desirable but not essential condition for accurate prediction (Bowen & Mortensen 1996). At Cowal Peninsula, wind speed correlation was weak for all recording sites except Cruach Buidhe. Wind direction correlation was also weak except at the Garrachra site. In the Manawatu Gorge area, weak correlations were found for wind speed at all except the Whitson Farm site, but all wind direction correlations were high (r >0.73).

TABLE 2–Correlation coefficients for relationships between the recording and reference sites in terms of wind variables at (a) Cowal Peninsula and (b) Manawatu Gorge.

Recording site	Correlation coefficient (r)	
	Wind speed	Wind direction
(a) Cowal Peninsula		
Cruach Buidhe	0.656	0.450
Bernice Gap	0.312	0.461
Garrachra	0.338	0.656
Glenshellish R.S.	0.413	0.433
Glenshellish Lower	0.343	0.029
(b) Manawatu Gorge		
North Range Road N	0.256	0.747
North Range Road S	0.315	0.841
Owen Farm	0.282	0.730
Whitson Farm	0.673	0.818
Pahiatua Track	0.503	0.829

Surface roughness

Surface roughness information was obtained from the Land Cover of Scotland 1988 maps (MLURI 1993) and the Vegetative Cover Map of New Zealand (Newsome 1987). Roughness length was determined from the European Wind Atlas (Troen & Petersen 1989). For each study area, land cover classes present and their assigned roughness length values are given in Table 3.

Terrain

Terrain data derived from digital terrain models were obtained from the British Ordnance Survey and the New Zealand Department of Survey and Land Information respectively. Values were converted into the format required for each model using the geo-statistics programme Surfer (Golden Software 1995).

Application of the Models

Identical information from the study areas was subjected to analysis by each of the three airflow models. Grid size and spacing used for each model are listed in Table 4. Data for all six sectors listed in Table 1 were analysed. A 1000-m-deep, neutrally-stratified, boundary

TABLE 3—Roughness length values assigned to each land or vegetative cover class in (a) the Cowal Peninsula and (b) the Manawatu Gorge study areas.

Land cover class	Roughness length, z_o (m)
(a) Cowal Peninsula	
Water surfaces	0.0004
Grasslands	0.03
Recent forest plantings	0.15
Forest stands up to 20 years old	0.5
Mature forest stands	1.0
(b) Manawatu Gorge	
Improved pasture	0.03
Unimproved pasture	0.03
Horticultural crops	0.05
Grassland and *Leptospermum* scrub	0.1
Pasture and broadleaved forest	0.1
Broadleaved forest and scrub	0.2

TABLE 4—Grid sizes and spacings for the Cowal Peninsula and Manawatu Gorge simulations.

Model	Cowal Peninsula		Manawatu Gorge	
	Grid size	Grid spacing (m)	Grid size	Grid spacing (m)
Flowstar	128 × 128	152	128 × 128	172
MSFD-PC	128 × 128	152	128 × 128	172
MS-Micro/3	256 × 256	76	256 × 256	86

layer was selected for operation of Flowstar, and mixing-length and higher-order closure schemes were tested separately in MSFD-PC analysis. Elevation of the upstream upper level was set at 20 m in MS-Micro/3 and MSFD-PC. This systematically reduced the height of terrain features in the study area by 20 m.

Processing of Actual Wind Data

Values for actual observations were normalised before comparison with predicted values. This was achieved by dividing wind speed at the recording site by wind speed at the reference site. Wind direction observations at each recording site were normalised by subtracting wind direction at the reference site. For the Cowal Peninsula area, the predicted wind speeds and directions were also adjusted so that the predicted and observed normalised wind speed and direction were the same at the reference site. This procedure was not possible in the Manawatu Gorge study because the reference site was located on the area of flat terrain to the north-west of the study area (i.e., in the upstream outer region of the modelling domain).

Model Validation

The models were evaluated by comparing normalised observed and predicted wind speeds and directions in both study areas. Model effectiveness was assessed quantitatively by calculating the root mean square error (RMSE) for each simulation as follows :

$$RMSE = \left[\frac{\sum_{i=1}^{N} (p_i - o_i)^2}{N} \right]^{1/2}$$

where o_i is the observed wind speed or direction at site i, p_i is the predicted wind speed or direction at the same site, and N is the number of observation sites over which the comparisons are performed. A non-dimensional prediction error, defined as the RMSE divided by the mean of the observed wind speeds (Barnard 1991), was also calculated and expressed as a percentage.

Fire Danger Rating

One of the most important components of the NZFDRS is the determination of Fire Danger Class Criteria (FDCC) from weather data. These Criteria are used by fire authorities as a basis for the presentation of standard messages about daily fire danger conditions over a broad area (Alexander 1994). Five classes are used (Table 5) to provide a general indication of the difficulty of fire control in "standard" fuel types (i.e., Forest or Grassland fuels). The potential impact of modelling error on fire danger rating was assessed by applying prediction errors from both point source and airflow model estimates of wind speed to actual data from three long-term New Zealand weather stations (Christchurch, Ohakea, and Rotorua—*see* Table 6). Each long-term dataset was used independently to compare actual and predicted average number of days allocated to each forest fire danger class.

TABLE 5–Minimum resources requirements for head fire containment in specified fire danger classes (after Alexander 1994).

Fire danger class	Fire intensity range (kW/m)	Minimum fire suppression resources required for direct head fire attack
Low	0–10	Hand crew.
Moderate	10–500	Hand crew and back-pack.
High	500–2000	Water under pressure and bulldozer.
Very High	2000–4000	Aircraft and long-term retardants likely to be effective. May be too dangerous for ground crews.
Extreme	> 4000	Head fire attack unlikely to be effective. Probably too dangerous for ground crews.

TABLE 6–Data sets used to test the effect of modelling error on fire danger rating.

Station name	Recording period	Number of years	Reason for selection
Christchurch Aero	1961–95	35	Representative of one of the most severe fire climates in New Zealand.
Ohakea Aero	1965–95	31	Nearest long-term station to the Manawatu Gorge area.
Rotorua Aero	1975–95	21	Representative of one of the less severe fire climates in New Zealand; 30 km from Kaingaroa Forest, the largest plantation forest in the country.

RESULTS

Cowal Peninsula

For each model, RMSE and prediction errors for wind speed and direction at Cowal Peninsula are listed in Table 7. Flowstar output was highly variable, with wind speed prediction errors over the six sectors ranging between 11% and 116%. Comparable MSFD-PC ranges were 26–39% (simple closure scheme) and 24–37% (higher order closure scheme), while for MS-Micro/3 the range was 20–32%. Although none of the models was outstanding, MS-Micro/3 wind speed estimates were the most accurate. Scatterplots showing relationships between observed normalised wind speed and predicted wind speed at each recording site (Fig. 5) indicated under-prediction by all the models at Cruach Bhuidhe. This site is on an exposed ridge forming the eastern side of Glenshellish Valley. Wind speed at Bernice Gap, just below the head of a hanging valley lying at right angles to Glenshellish, was under-predicted by MS-Micro/3 and MSFD-PC but over-predicted by Flowstar. Wind speeds at Glenshellish Restock and Garrachra were over-predicted by all models. Garrachra is on the lee side of a hill where flow separation may have affected the results. The reason for Flowstar over-prediction at Glenshellish Restock is not apparent.

None of the models predicted wind direction accurately, with mean RMSE values ranging between 79° and 93° (Table 7b). MS-Micro/3 was the best performer and Flowstar gave the

TABLE 7–Cowal Peninsula airflow simulation root mean square errors and prediction errors of (a) normalised wind speeds and (b) normalised wind directions.

(a) Normalised wind speeds

Case	Flowstar		MSFD-PC (Simple closure scheme)		MSFD-PC (Higher-order closure scheme)		MS-Micro/3	
	RMSE (m/s)	Prediction error (%)	RMSE (m/s)	Prediction error (%)	RMSE (m/s)	Prediction error (%)	RMSE (m/s)	Prediction error (%)
1	0.770	97	0.222	28	0.219	28	0.210	27
2	0.101	13	0.198	26	0.184	24	0.155	20
3	0.136	17	0.253	32	0.240	30	0.190	24
4	0.083	11	0.263	34	0.259	34	0.202	26
5	0.957	116	0.320	39	0.308	37	0.263	32
6	0.864	91	0.353	37	0.351	37	0.295	31
Mean	0.418	51	0.271	33	0.261	32	0.213	26

(b) Normalised wind directions

Case	Flowstar RMSE (degrees)	MSFD-PC (Simple closure scheme) RMSE (degrees)	MSFD-PC (Higher-order closure scheme) RMSE (degrees)	MS-Micro/3 RMSE (degrees)
1	83	72	72	66
2	99	76	75	92
3	74	88	89	55
4	105	88	89	65
5	108	100	100	77
6	85	91	91	109
Mean	93	86	87	79

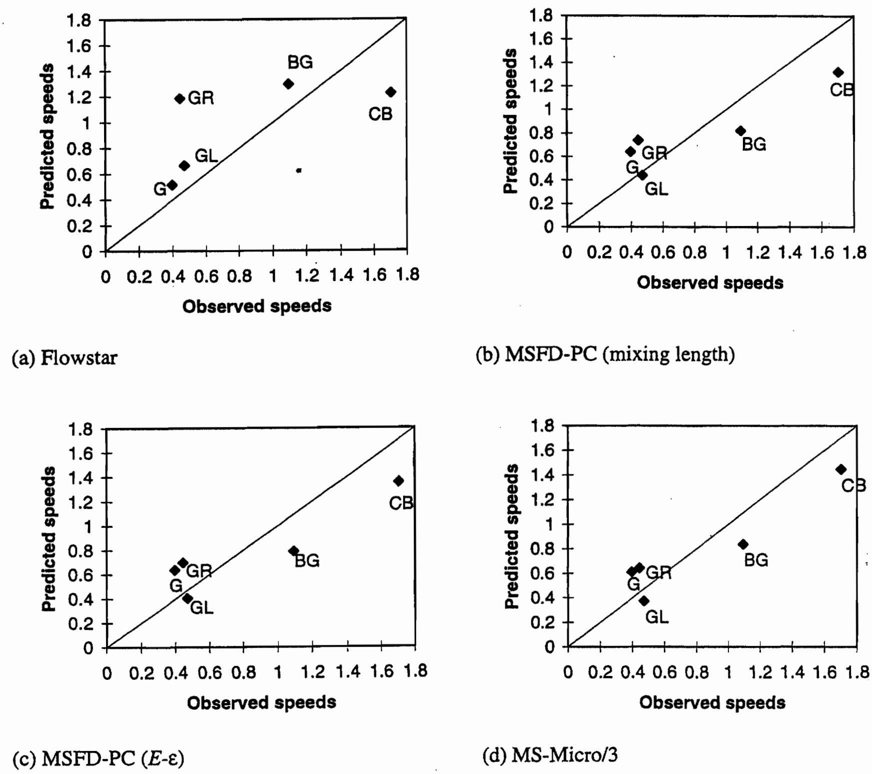


FIG. 5–Comparison of the observed normalised wind speeds at the Cowal Peninsula sites with those predicted by (a) Flowstar, (b) MSFD-PC with a mixing-length closure scheme, (c) MSFD-PC with an E–ε closure scheme, and (d) MS-Micro/3. Each value is the mean of prediction errors for six 10° wind direction sectors.

poorest results. In a study by Barnard (1991), output from airflow models was assessed by comparing prediction errors with those from simulations in which the wind field was assumed to be uniform over the study area and equal to that observed at the reference site. Under these conditions the RMSE for the whole Cowal Peninsula study area was 63°. Since all of the RMSE values in the airflow simulations exceeded 75°, the models did not provide insight into the influence of topography on wind direction in the Cowal Peninsula area.

Manawatu Gorge

Wind speed prediction errors in the Manawatu Gorge study area were similar for all three models (Table 8a). Means for the six sectors ranged between 28% (MS-Micro/3) and 38% (Flowstar). Magnitudes of wind speed prediction errors were similar to those in the Cowal Peninsula study area, but RMSEs were larger for the Manawatu Gorge simulations. Scatterplots of observed and predicted wind speeds (Fig. 6) indicated under-prediction at all recording sites by all models. Under-prediction was greatest for the Pahiatua Track site. Reid (1985), in a study of this particular ridge, suggested that high wind speeds are likely to be localised in the section near the Pahiatua Track due to narrowness of the ridge at this point and also to lateral concentration of the flow up the valley lying to the north-west.

TABLE 8–Manawatu Gorge simulation root mean square errors and prediction errors of (a) normalised wind speeds and (b) normalised wind directions.

(a) Normalised wind speeds

Case	Flowstar		MSFD-PC (Simple closure scheme)		MSFD-PC (Higher-order closure scheme)		MS-Micro/3	
	RMSE (m/s)	Prediction error (%)	RMSE (m/s)	Prediction error (%)	RMSE (m/s)	Prediction error (%)	RMSE (m/s)	Prediction error (%)
1	1.070	54	0.983	49	0.963	48	0.966	48
2	0.894	45	0.894	45	0.865	44	0.854	43
3	0.639	35	0.673	37	0.647	36	0.605	33
4	0.294	24	0.278	22	0.274	22	0.277	22
5	0.536	35	0.371	24	0.344	22	0.295	19
6	0.861	47	0.633	34	0.606	33	0.561	30
Mean	0.657	38	0.582	33	0.555	32	0.469	28

(b) Normalised wind directions

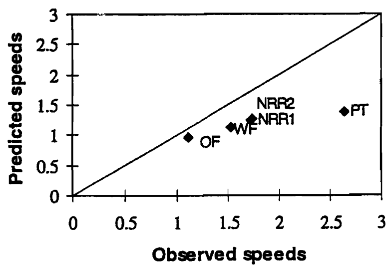
Case	Flowstar RMSE (degrees)	MSFD-PC (Simple closure scheme) RMSE (degrees)	MSFD-PC (Higher-order closure scheme) RMSE (degrees)	MS-Micro/3 RMSE (degrees)
1	33	36	36	21
2	38	38	38	23
3	35	34	34	22
4	20	24	24	15
5	15	14	14	10
6	10	12	12	10
Mean	27	31	28	20

In Flowstar and MSFD-PC simulations, RMSEs for wind speed were lowest when wind direction at the reference site was between 280° and 290°. This was because normalised wind speed for this sector at the reference site (i.e., unity) was closest to the average of normalised observed wind speeds at the five recording sites. Using Barnard's (1991) suggestion that model error would be reduced by selection of a reference site with wind speed closer to the mean for all recording sites, the North Range Road South station was substituted as the reference site. This reduced the overall prediction error from 33% to 17%.

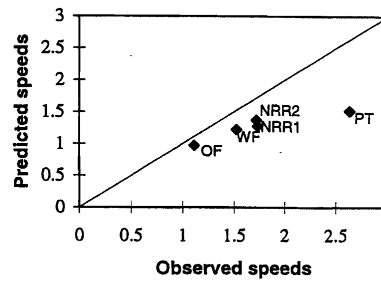
The influence of topography on wind direction in the Manawatu Gorge area was smaller than in the Cowal Peninsula area, average deviations from direction at the reference site being 24° and 72° respectively. The RMSEs of the simulations varied between 20° and 31°. The RMSE for a simulation in which wind direction over the study area was assumed to be uniform and equal to that at Palmerston North was 23°. Only the MS-Micro/3 simulation had an RMSE lower than this value.

Fire Danger Rating

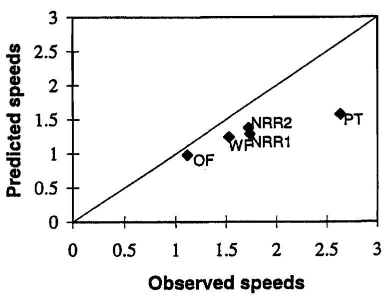
The present New Zealand Fire Danger Rating System uses wind speed prediction errors associated with data from a single point source. When wind speeds over the two study areas



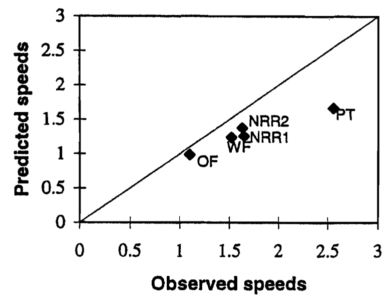
(a) Flowstar



(b) MSFD-PC (mixing-length)



(c) MSFD-PC (E-ε)



(d) MS-Micro/3

FIG. 6—Comparison of the observed normalised wind speeds at the Manawatu Gorge sites with those predicted by (a) Flowstar, (b) MSFD-PC with a mixing-length closure scheme, (c) MSFD-PC with an E–ε closure scheme, and (d) MS-Micro/3. Each value is the mean of prediction errors for six 10° wind direction errors.

were assumed to be uniform and equal to those at the reference sites, errors of 67% at Cowal Peninsula and 50% at Manawatu Gorge were observed. The results of applying wind speed errors of ±50% and ±25% to the actual number of days in each fire danger class at Christchurch, Ohakea, and Rotorua are shown in Table 9. The effect of over- or under-prediction of wind speed was greatest for the Very High and Extreme fire danger classes at all three weather stations. When the wind speed prediction error at Christchurch was ±50%, the predicted number of days in the Extreme class was 16.4 fewer or 24.1 more than the actual number of 21.3. For a prediction error of ±25% the number of days was 9.4 fewer or 11.7 days more. At Rotorua, which has a much less severe fire climate, the predicted number of days in the Extreme class was only 0.2 lower or 1.8 more than the 0.5 days actually experienced.

DISCUSSION

Similar results for wind speed prediction produced by the MS-Micro/3 and MSFD-PC models undoubtedly reflected their common theoretical basis. Wind speeds predicted with either the simple or the high-order closure scheme in the MSFD-PC model were very similar. Beljaars *et al.* (1987) remarked that velocity changes are insensitive to the type of closure scheme employed. Models with mixing-length closure schemes can therefore be regarded as adequate for wind speed prediction. Overall, the MSFD-PC model did not perform as well

TABLE 9—Effect of 25% and 50% wind speed prediction errors on the mean annual number of days allocated to specific fire danger classes at three New Zealand weather stations.

	Wind speed prediction error				
	–50%	–25%	Actual	+25%	+50%
Christchurch					
Low	215.1	197.3	181.7	168	155.3
Moderate	108.6	105.6	102.5	98.9	96.2
High	29.2	38	42	43.4	43.8
Very High	7.3	12.4	17.8	22	24.6
Extreme	4.9	11.9	21.3	33	45.4
Ohakea					
Low	271.8	249.2	227.3	209.4	194.3
Moderate	83.5	92.9	99.7	101.8	103.3
High	9.4	18.1	25.8	31.8	36.5
Very High	0.6	4	7.3	11.9	14.8
Extreme	0	1	5.1	10.5	16.4
Rotorua					
Low	302.4	285.9	275.6	261.3	248.6
Moderate	59.8	70.6	76.8	84.3	89.8
High	2.9	8	10.6	15	18.5
Very High	0.1	0.5	1.6	3.2	5
Extreme	0	0.3	0.5	1.4	3.3

as MS-Micro/3. This contradicts the finding of a study by Beljaars *et al.* (1987) in which models with a higher-order closure scheme gave a slightly better performance.

The magnitudes of wind speed prediction errors for all models except Flowstar (26–33% at Cowal Peninsula; 28–33% at Manawatu Gorge) were similar to those found by Barnard (1991) for the Altamont Pass site (28.4%), but much higher than the 7% found by Walmsley *et al.* (1990) for Blashaval Hill and the 8–10% found by Barnard (1991) for Askervein Hill. At the latter sites, the topography consisted of an isolated hill surrounded by relatively flat terrain. In the Cowal Peninsula and Manawatu Gorge simulations, large errors in predicted wind speed can probably be attributed to the influence of surrounding terrain on free-stream airflow. Barnard (1991) attributed large prediction errors to violation of the uniform free-stream flow assumption. The large number of observations in his study made post-processing of the results possible. Using data from six of the observation sites he obtained a correction factor that reduced prediction error to approximately 8%. The sparse distribution of wind observation stations available for fire danger rating means that, in most areas, data for modelling are derived from only one station. In complex terrain, the modelled wind speed used as an input into the equations for fire danger rating is consequently likely to be in error by approximately 25–30%. Although the study was not sufficiently comprehensive to make a firm distinction between the models, based on processing time and results obtained MS-Micro appeared to be the best model for providing wind speed information for use in fire danger rating.

The use of airflow models is likely to provide a better assessment of fire danger over broad areas of complex terrain than single point source wind data. Although lowest errors associated with wind speed predictions were approximately half as great as those encountered without simulation, the implications in terms of fire danger rating are still considerable, especially at sites (such as Christchurch and Ohakea) where the fire climate is severe. Forests are often closed to the public during periods of Very High or Extreme fire danger, and in some areas silvicultural and harvesting operations may be interrupted. Assuming that Ohakea Aero data are relevant to the Manawatu Gorge area and that, on average, 5 Extreme fire danger days are experienced each year, over-prediction of wind speed by 50% could incur unnecessary prevention and preparedness costs on 11 additional days. While an over-assessment of fire danger may result in the inefficient use of resources, under-estimation can lead to greater risk of an ignition and result in inadequate preparation if a fire does start under Very High or Extreme conditions. The accuracy of fire danger rating can be improved by the use of airflow models, and the reduced level of over-prediction in the Very High and Extreme danger classes may be acceptable for areas with complex terrain where the fire climate is severe.

The effect of wind speed simulation on error margins for fire danger rating, together with the effect of reference site selection at Manawatu Gorge, suggests that a broad zone estimate of danger rating calculated from single point sources (generally a remote automatic weather station) could be subject to serious error if wind speed was not representative over the whole area of interest. It is therefore very important that the location of weather stations should be related to local topography. Compliance with weather station standards (e.g., Turner & Lawson 1978) is important for collection of representative data.

There is no detailed information published about wind direction modelling on simple terrain. Fosberg *et al.* (1976) applied a linear microscale model to datasets from the Cascade Mountains in Oregon and central California and found an RMSE for wind direction of 43°. This value was significantly lower than those associated with model testing at Cowal Peninsula (where wind direction was related to topography), but nearly double those in the Manawatu Gorge comparisons. Although wind speed is usually more important than wind direction during determination of fire danger rating, wind direction causing a fire to move uphill can be critical. This is because the effect of slope is similar to that of wind if flames are closer to the fuels than the front and preheating results (Cheney 1981). Fire danger rating in areas with long slopes of similar aspect could be improved if wind vectors were used to adjust predicted fire behaviour and fire danger assessments. This would allow identification of sites where the effects of wind and slope are not cumulative. The models evaluated in this study did not predict wind direction with the accuracy that would be needed in this context.

CONCLUSIONS

Comparisons between model predictions and actual observations in the Cowal Peninsula and Manawatu Gorge areas showed that average wind speed prediction errors, calculated from data for five stations, varied between 26% and 51%. Mean values were greater than those obtained elsewhere for areas of less complex terrain, but similar to those obtained for comparable topography. The mean prediction error for the best performing model (MS-Micro/3) was approximately half of that observed when wind speeds over the two study areas were assumed to be uniform and equal to those at the reference sites. The models did not provide accurate estimates of wind speed direction in complex terrain.

Application of a 50% wind speed prediction error had a marked effect on designation of the number of days in Very High and Extreme fire danger classes in an area with a severe fire climate. The effect of a wind speed prediction error of 25% was much less pronounced. In areas with greater risk potential and complex terrain, prediction of wind speed using the Jackson-Hunt linear microscale models evaluated in this study will improve the accuracy of forest and rural fire danger assessment. Further reduction of prediction errors will increase the efficiency of standby resource deployment.

ACKNOWLEDGMENTS

This study was funded by the Foundation for Research Science and Technology (FRST) under contract 4425. Dr Tony Bowen, Dr Steve Reid, Dr Ruth Gadgil, and Mr Grant Pearce provided comments and suggestions on the manuscript. Alex Hawke and Alen Slijepcevic assisted with calculation of fire danger rating.

REFERENCES

ALEXANDER, M.E. 1994: Proposed revision of fire danger class criteria for forest and rural areas in New Zealand. National Rural Fire Authority, Wellington. 73 p.

BARNARD, J.C. 1991: An evaluation of three models designed for siting wind turbines in areas of complex terrain. *Solar Energy 46*: 283–294.

BELJAARS, A.C.M.; WALMSLEY, J.L.; TAYLOR, P.A. 1987: A mixed spectral finite-difference model for neutrally stratified boundary-layerflow over roughness changes and topography. *Boundary-Layer Meteorology 38*: 273–303.

BOWEN, A.J.; MORTENSEN, N.G. 1996: Exploring the limits of the Wind Atlas Analysis and Application Program. Pp.584–587 *in* Proceedings European Wind Energy Conference, Gothenburg, Sweden, 20–24 May.

CHENEY, N.P. 1981: Fire behaviour. Pp.151–175 *in* Gill, A.M.; Groves, R.H.; Noble, I.R. (Ed.) "Fire and the Australian Biota". Australian Academy of Science, Canberra, Australian Capital Territory.

COUNTRYMAN, C.M. 1972: The fire environment concept. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, California. 12 p. [reprinted as National Fire Equipment System (NFES) 2166 by National Wildfire Coordinating Group, Boise Interagency Fire Center, Boise, Idaho].

FOSBERG, M.A.; MARLATT, W.E.; KRUPNAK, L. 1976: Estimating airflow patterns over complex terrain. *USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado. Research Paper RM-162.* 17 p.

GOLDEN SOFTWARE 1995: "Surfer - Surface Mapping System Version 6.01". Golden Software Inc., Golden, Colorado.

HANNAH, P. 1993: Application of wind modelling techniques in complex terrain. Ph.D. thesis, University of East Anglia.

HAYES, P.S.; FERGUSON, S.A.: Surface wind modelling for resource managers. USDA Forest Service, Pacific Northwest Research Station, Seattle, Washington (in prep.)

HUNT, J.C.R.; LEIBOVICH, S.; RICHARDS, K.J. 1988: Turbulent shear flow over low hills. *Quarterly Journal of the Royal Meteorological Society 114*: 1435–1470.

HUNT, J.C.R.; RICHARDS, K.J.; BRIGHTON, P.W.M. 1988: Stably stratified shear flow over low hills. *Quarterly Journal of the Royal Meteorological Society 114*: 859–886.

INGLIS, D.W.F.; CHOULARTON, T.W.; STROMBERG, I.M.F.; GARDINER, B.A.; HILL, M. 1995. Testing of a linear airflow model for flow over complex terrain and subject to stable, structured stratification. Pp.88–112 *in* Coutts, M.P.; Grace, J. (Ed.) "Wind and Trees". Cambridge University Press, Cambridge.

JACKSON, P.S.; HUNT, J.C.R. 1975: Turbulent wind flow over a low hill. *Quarterly Journal of the Royal Meteorological Society 101*: 929–955.

LATHAM, D. 1993: Weather data requirements for behaviour based fire danger rating systems. Pp.156–163 *in* Proceedings, 12th Conference on Fire and Forest Meteorology, 25–29 October, Jekyll Island, Georgia. *Society of American Foresters, Bethesda, Maryland, SAF Publication 94-02.*

LEE, B.S.; ANDERSON, K.R. 1989: A spatial approach for forest fire preparedness planning. Pp.339–345 *in* Maciver, D.C; Auld, H.; Whitewood, R. (Ed.) Proceedings, 10th Conference on Fire and Forest Meteorology, Ottawa, Canada.

MASON, P.J.; SYKES, R.I. 1979: Flow over an isolated hill of moderate slope. *Quarterly Journal of the Royal Meteorological Society 105*: 383–395.

MLURI 1993: "The Land Cover of Scotland 1988: Executive Summary". The Macaulay Land Use Reseach Institute, Aberdeen, Scotland. 39 p. + 1 map sheet.

NEWSOME, P.J.F. 1987: The vegetative cover of New Zealand. *Ministry of Works and Development, Water and Soil Miscellaneous Publication No.112.* 153 p. + 2 map sheets.

PHYSICK, W.L. 1985: Review: mesoscale modelling in complex terrain. *Earth-Science Reviews 25*: 199–235.

REID, S.J. 1985: Manawatu wind studies: speed-up over a ridge. *Weather and Climate 5*: 52–63.

SHERMAN, C.A. 1978: A mass-consistent model for wind fields over complex terrain. *Journal of Applied Meteorology 17*: 312–319.

STOCKS, B.J.; LAWSON, B.D.; ALEXANDER, M.E.; VAN WAGNER, C.E.; McALPINE, R.S.; LYNHAM, T.J.; DUBÉ, D.E. 1989: The Canadian Forest Fire Danger Rating System: an overview. *Forestry Chronicle 65*: 450–457.

TAYLOR, P.A.; WALMSLEY, J.L.; SALMON, J.R. 1983: A simple model of neutrally stratified boundary-layer flow over real terrain incorporating wavenumber-dependent scaling. *Boundary Layer Meteorology 26*: 169–189.

TEUNISSEN, H.W.; SHOKR, M.E.; BOWEN, A.J.; WOOD, C.J.; GREEN, D.W.R. 1987: Askervein Hill Project: Wind-tunnel simulations at three length scales. *Boundary-Layer Meteorology 40*: 1–29.

TROEN, I.B.; PETERSEN, E.L. 1989: "European Wind Atlas". Risø National Laboratory, Roskilde, Denmark. 656 p.

TURNER, J.A.; LAWSON, B.D. 1978: Weather in the Canadian Forest Fire Danger Rating System: a user guide to national standards and practices. *Canadian Forestry Service, Pacific Forestry Research Centre, Victoria, British Columbia, Information Report BC-X-177.* 40 p.

WALMSLEY, J.L.; TAYLOR, P.A.; KEITH, T. 1986: A simple model of neutrally stratified boundary-layer flow over complex terrain with surface roughness modulations (MS3DJH/3R). *Boundary-Layer Meteorology 36*: 157–186.

WALMSLEY, J.L.; WOOLRIDGE, D.; SALMON, J.R. 1993: MS-Micro/3 user's guide. *Atmospheric Environment Service, Downsview, Ontario, Canada, Report ARD-90-008.*

WALMSLEY, J.L.; TROEN, I.B.; LALAS, D.P.; MASON, P.J. 1990: Surface-layer flow in complex terrain: comparisons of models and full-scale observations. *Boundary-Layer Meteorology 52*: 259–281.

VAN WAGNER, C.E. 1987: Development and structure of the Canadian Forest Fire Weather Index System. *Canadian Forestry Service, Ottawa, Ontario, Forestry Technical Report 35.* 37 p.