Fire Research Report

Prediction of Fire Weather and Fire Danger

NIWA

June 2007

This project investigated methods for forward prediction of severe fire weather. It aimed to bridge the gap between current forecasts of day-to-day changes and climate forecasts of changing risks over the coming months, so that assessments of fire weather severity can be made earlier than at present. The research used innovative methods developed by NIWA for forecasting fire risk from two to four weeks ahead for fire risk regions that utilises a set (or "ensemble") of weather forecast model runs that capture the inherent uncertainty in the atmospheric circulation. The scheme predicts the likely range of temperature (daily maximum and minimum, soil), average wind speed, daily rainfall and solar radiation at 70 sites, with rainfall and temperature at over 100 sites, from one day out to two weeks, with an extension that estimates temperate and rainfall for a month out. To go to monthly forecasts, the predictions for the first two weeks of the 30-day period are used to estimate the probability distribution of outcomes for the whole 30-day period. Here, we assess the utility of this scheme to predict fire weather, described using the fuel moisture codes and fire behaviour indices contained within the Fire Weather Index (FWI) System module of the NZFDRS.

(Also see report #72)

New Zealand Fire Service Commission Research Report Number 83
ISBN Number 978-1-877349-62-1 (on-line)
ISBN Number 978-1-877349-63-8 (paperback)

Prediction of Fire Weather and Fire Danger

NIWA Client Report: AKL2007-034
June 2007

NIWA Project: FSS07101

Prediction of Fire Weather and Fire Danger

Authors
Jim Renwick[1]
Jim Salinger[1]
Xiaogu Zheng[1]
Grant Pearce[2]

Prepared for

New Zealand Fire Service Commission

NIWA Client Report: AKL-2007-034

June 2007

NIWA Project: FSS07101

[1]National Institute of Water & Atmospheric Research Ltd

269 Khyber Pass Road, Newmarket, P O Box 109695, Auckland

Phone +64-9-375 2050, Fax +64-9-375 2051

www.niwa.co.nz

[2]Ensis

Bushfire Research Group

P. O. Box 29-237, Fendalton, Christchurch, New Zealand

www.ensisjv.com

Contents

Reviewed by:

Craig Thompson

Approved for release by:

Ken Becker

Formatting checked

Executive Summary

New Zealand experiences around 3000 vegetation wildfires each year that burn around 7000 hectares of rural lands. Strong winds, high temperatures, low humidity and seasonal drought can combine to produce dangerous fire weather situations. These features fluctuate seasonally, and from year to year.

Assessment of the effect of fire weather (and other fire environment factors of fuels and topography) on potential fire occurrence and fire behaviour is assisted by the use of the New Zealand Fire Danger Rating System (NZFDRS), which is based on the Canadian Forest Fire Danger Rating System (CFFDRS). This project aims to provide methods for forward prediction of severe fire weather, described using the fuel moisture codes and fire behaviour indices contained within the Fire Weather Index (FWI) system module of the NZFDRS, for the two to four week period.

Both the Meteorological Service of New Zealand and NIWA have been providing seasonal forecast products for several years, and these have infrequently included passing reference to fire danger. The NIWA-led 'Integrated Climate and Fire Season Severity Forecasting' programme has provided forecasts of regional fire danger over New Zealand from 2000 – 2004. MetService developed a method for producing medium range forecasts of fire weather indices that showed skill as far as day 10. However, the anticipated ability of the forecasts to add situation-dependent probabilistic information was not found.

NIWA has developed a scheme that predicts the likely range of temperature (daily maximum and minimum, soil), average wind speed, daily rainfall and solar radiation at 70 sites, with rainfall and temperature at over 100 sites, from one day out to two weeks, with an extension that estimates temperate and rainfall for a month out. This scheme uses a set (or "ensemble") of weather forecast model runs that capture the inherent uncertainty in the atmospheric circulation. To go to monthly forecasts, the predictions for the first two weeks of the 30-day period are used to estimate the probability distribution of outcomes for the whole 30-day period. Here, we assess the utility of this scheme to predict elements of the FWI system.

FWI System components were related to observed and simulated daily climate information for four Northland sites and five Canterbury sites. Multivariate relationships between elements of the FWI system, and available climate variables and analyses of the large scale atmospheric circulation were developed.

Regional indices used included five 1000 hPa height pressure patterns over New Zealand, five 850 hPa

temperature fields, regional mean means of westerly and southerly wind speeds at 1000 hPa height and regional vorticity, a proxy for storminess and upward motion.

The main findings were that:

- For the FWI components for all Northland sites, the strongest relationships were found for Fine Fuel Moisture Code (FFMC) and the Fire Weather Index (FWI) value itself with analysed regional vorticity (a proxy for storminess, vertical motion and rainfall) at all stations, and FFMC with rainfall, minimum temperature and solar radiation at the nearest climate station. For Northland, anticyclonic conditions coupled with enhanced southerly winds are associated with higher FFMC and FWI values. The variance accounted for in regressions on FFMC and FWI typically ranged from 15 to 25%, for contemporary relationships (today's FWI System values from today's weather). This level of skill suggests limited skill in forecast mode, on the order of 10-15% explained variance.

- At Canterbury sites, relationships with FWI System components were strongest with analysed regional circulation indices. The best relationships were found between FFMC, FWI and Daily Severity Rating (DSR) with westerly wind strength, and for more eastern stations with higher atmospheric temperature. Nearest climate station maximum temperatures and earth temperatures were also well related to FFMC, FWI and DSR, notably in those stations farthest east. In Canterbury, stronger westerly winds and higher temperatures are associated with higher FFMC and FWI. The variance accounted for in regressions on FFMC and FWI typically ranged from 20 to 30%, for contemporary relationships (today's FWI values from today's weather). This level of skill, somewhat higher than that found for Northland, suggests some skill in forecast mode, on the order of 15-20% explained variance.

- Given the level of skill found in contemporary diagnostic relationships between weather/climate variables and elements of the FWI System, it seems likely that individual daily predictions of FWI components would not exhibit useful skill in an operational sense. Similarly, extending the approach to monthly predictions, given the levels of skill found here, is also unlikely to produce operationally useful results. It is however possible that weekly (or other multi-day) averages of FWI components may be skilfully predicted from averaged weather information. It would be worth pursuing this approach in future years' research.

1. Introduction

Even though New Zealand does not have one of the most severe fire climates in the world, the country still experiences around 3000 rural vegetation fires each year that burn some 7500 ha of rural lands[1]. Strong winds, often associated with high temperatures, low humidity and seasonal drought, can combine to produce dangerous fire weather situations. To effectively manage this risk, New Zealand fire managers require knowledge of the likely severity of seasonal fire weather and fire danger conditions at a range of scales from short-term forecasts to long-range seasonal predictions. It is useful to have results that can be utilised immediately as well as providing a platform from which future research can be built.

Currently medium range forecasts of daily climate elements show skill as far as ten days ahead. Recently it has been found that weather elements can be skilfully predicted in a probabilistic sense out almost two weeks, and that such forecasts can indicate tendencies for the coming month with a modest amount of skill. The aim is to bridge the gap between forecasts of day-to-day changes to a climate forecast of changing risks over the coming months, so that assessments of fire weather severity can be made earlier than at present. This would also provide objective trigger points for the implementation of prevention programmes, including the imposition of rural fire restrictions and prohibitions, and mounting of national and regional publicity campaigns, and increase fire detection regimes in rural areas so that fires are reported and responded to more rapidly.

2. Scope of the Study

This report summarises research completed by NIWA and Ensis as part of the joint NIWA-Forest Research project "Prediction of Fire Weather and Associated Fire Danger". The joint project aimed to investigate methods for forward prediction of severe fire weather. It combines the outcomes from previous NIWA research into the prediction of fire season severity and improved regional fire danger forecasts for New

[1] From statistics for the period 1993/94-2002/03 produced by the National Rural Fire Authority, based on the Annual Return of Fires form completed by New Zealand fire authorities.

Zealand and complementary research undertaken by Ensis (then Forest Research) to develop a national fire climatology database and associated analytical tools.

This part of the joint project, “Two to four week prediction of fire extremes” aims to better utilise extended-range weather forecasts now routinely done on the one- to two-week time scale. This aims to produce probabilistic predictions of factors influencing fire risk up to a month ahead. The key steps in this study included:

- Relating Fire Weather Index (FWI) System components from observed and simulated daily climate information to regional scale weather variables predicted by the US National Weather Service global forecasting model, for sites in Northland and Canterbury;

- Developing multivariate relationships between FWI and its components and available weather/climate variables;

- Testing the derived relationships with real-time forecast model output; and

- Presentation of the results and assessment of the feasibility of implementation of a FWI prediction scheme for key regions in New Zealand.

3. Background

3.1 Fire danger rating in New Zealand

Assessment of the effect of fire weather (and other fire environment factors of fuels and topography) on potential fire occurrence and fire behaviour in New Zealand is assisted by the use of the New Zealand Fire Danger Rating System (NZFDRS) (Fig. 1a), which is based on the Canadian Forest Fire Danger Rating System (CFFDRS). The NZFDRS is used by New Zealand fire authorities to assess the probability of a fire starting, spreading and doing damage. New Zealand’s adoption and continued adaptation of the CFFDRS has been described by Fogarty *et al.* (1998) and Anderson (2006)..

The Fire Weather Index (FWI) subsystem of the CFFDRS (Van Wagner 1987) was adopted by the former New Zealand Forest Service in 1980. Based solely on weather observations, the FWI System (Fig. 1b) provides numerical ratings of relative ignition potential and fire behaviour which can be used as guides in a wide variety of fire management activities including (after Alexander 1992):

- prevention planning (e.g., informing the public of pending fire danger, regulating access and risk associated with public and industrial use of forest and rural areas);
- preparedness planning (e.g., level of readiness and pre-positioning of suppression resources);
- detection planning (e.g., lookout manning and aerial patrol routing);
- initial attack dispatching;
- suppression tactics and strategies on active wildfires; and
- prescribed fire planning and execution.

Daily observations made at noon local standard time of temperature, relative humidity, wind speed, and 24-hour accumulated rainfall recorded by a network of remote automatic weather stations located around the country are used to compute values of the three fuel moisture codes and three fire behaviour indexes. These may be determined from tables (e.g., Anon. 1993) or by computer calculation (Van Wagner and Pickett 1985). The New Zealand Fire Weather Monitoring System (FWSYS) is described in more detail by Pearce and Majorhazi (2003).

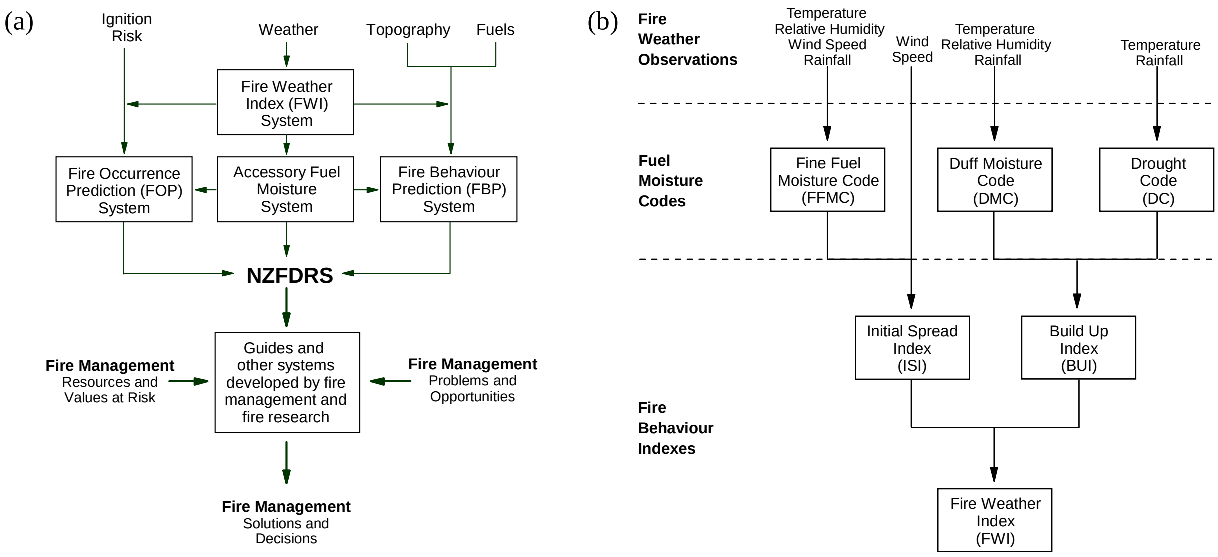

Figure 1. Simplified structure diagrams for (a) the New Zealand Fire Danger Rating System (NZFDRS), illustrating the linkage to fire management actions (after Fogarty *et al*. 1998); and (b) the Fire Weather Index (FWI) System (after Anon. 1993).

3.2 Fire climate research

The value of fire climatological information for fire management is evidenced by the vast number of studies and variety of applications in the literature. A significant number of studies have attempted to use fire climatologies to describe fire activity (e.g., Harrington *et al*. 1983). Fire danger climatologies have also been used to show seasonal trends in fire danger (McAlpine 1990) including comparison of the severity of individual fire seasons for particular stations (e.g., Harvey *et al*. 1986), to determine length of fire season (Wotton and Flannigan 1993) and define fire climate regions (e.g. Simard 1973). They have also been used to define impacts of El Nino-Southern Oscillation events (e.g. Williams 1998) and climate change (e.g. Wotton *et al*. 1998). Perhaps more importantly, fire climatologies have been used to develop systems for the full range of fire management activities, including prevention (OMNR 1989, Borger 1997), preparedness (Gray and Janz 1985, Fogarty and Smart 1994), fire suppression (Andrews *et al*. 1998, Fogarty and Slijepcevic 1998), and prescribed fire planning (Andrews and Bradshaw 1990).

In trialling the FWI System prior to its introduction, Valentine (1978) compared fire season climatologies for British Columbia and New Zealand, and Cooper and Ashley-Jones (1987) used fire danger class frequencies to investigate the economics of fire prevention activities. Pearce (1996) produced a fire climatology for 20 weather stations and presented long-term average and extreme values for both weather inputs and fire danger components in a summary table for each station. In an effort to improve knowledge on the fire climate of New Zealand, the Pearce (1996) study was recently updated and extended by Ensis under the previous NZFSC-funded project 'Fire Danger Climatology Analyses and Tools' to include fire climate summaries for 127 weather station locations (Pearce *et al*. 2003). Summary statistics for each station were used to identify the individual weather stations and geographic regions with the most severe fire climates. Research by Ensis, conducted under the NIWA-led "Prediction of Fire Season Severity", also developed an analytical tool for predicting fire season severity based on past seasons (Pearce and Moore 2004), while the "Impact of Climate Variability and Change on Seasonal Fire Danger" project documented the impact of climate change on future fire danger (Pearce *et al*. 2005). As part of the present project, "Prediction of Fire Weather and Associated Fire Danger", Ensis is continuing to describe New Zealand's fire climate by investigating the effects of annual and decadal variability, described by the El Niño-Southern Oscillation (ENSO) and Interdecadal Pacific Oscillation (IPO), on seasonal fire danger (Pearce *et al*. 2007).

Recent research by NIWA undertaken under the NZFSC-funded project 'Integrated Climate and Fire Season Severity Forecasting' identified definite links between weather, climate and fire season severity for 21 locations, with predictive relationships being established for seasonal and monthly fire severity (Heydenrych *et al*. 2001a,b). Detailed relationships were identified between global (e.g. El Niño and La Niña) and regional climate elements (e.g., regional wind circulation and weather types) and monthly (MSR) and seasonal (SSR) fire severity ratings. At eastern sites, variants of stronger westerly quarter flow across New Zealand are the most important parameter promoting higher SSR. For the small sample of sites sheltered from easterly flow, variants of weaker westerlies or above average easterly quarter airflow produced above average SSRs. In 2001, the programme also identified 15 fire climate regions (Fig. 2a) based on the response of severity ratings to various climate predictors (Heydenrych and Salinger 2002, Salinger *et al*. 2002). Seven fire regions occur in each of the North and South Islands, with a further region straddling Cook Strait. For each region, the key linkages between fire severity rating and climate predictors were identified. In 2002, strong relationships were found between Daily Severity Ratings

(DSR) and daily and monthly climate variables, for two regions, Northland and Coastal Mid/South Canterbury (Gosai *et al*. 2003). This work was extended to all the other fire climate regions (see Fig. 2a), together with work to complete the classification for the improved management of regional fire dangers (Gosai *et al.* 2004, Griffiths 2004).

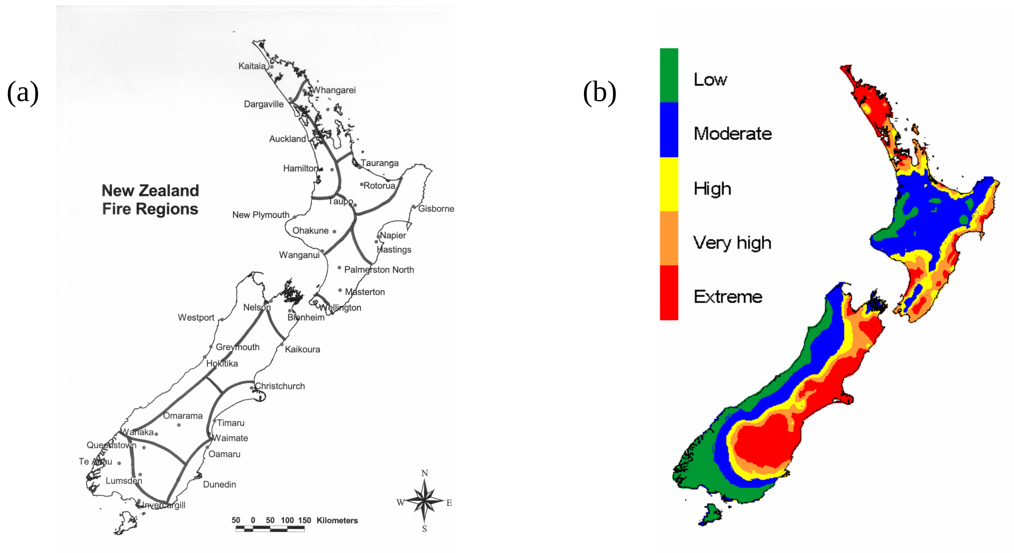

Figure 2. Maps of (a) New Zealand climate regions identified in the fire danger climatology analysis of Heydenrych and Salinger (2002); and (b) forecast fire danger for the end of January 2004 based on seasonal predictions (NIWA 2004).

3.3 Fire danger forecasting

Both the Meteorological Service of New Zealand (MetService) and NIWA have been providing seasonal forecast products for several years, and these have infrequently included passing reference to fire danger (e.g., Auer 1997, NIWA 1999). Utilising the results of research into factors contributing to fire season severity, the NIWA-led

'Integrated Climate and Fire Season Severity Forecasting' programme has provided scenarios and forecasts of regional fire danger (NIWA 2004) over New Zealand from 2000 - 2004 (see NIWA 2004; see Fig. 2b) so that the NRFA, together with local fire authorities, can prepare and deploy resources. The forecasts are publicly available and posted on the National Rural fire Authority's (NRFA) internet site[2]. This was the first time that seasonal fire danger scenarios tailored specifically to fire danger have been provided in New Zealand.

Research completed by MetService as part of the NZFSC-funded project "Forecast Fire Weather Indices for Fire Danger Assessment" resulted in production of a fire weather forecasting tool, known as MetConnect Fire, that combines forecasted data from MetService's mesoscale weather prediction model with FWI System calculations to provide spot forecasts for specific weather station locations. Initially the system produced forecasted hourly fire danger data (i.e., FFMC, ISI and FWI) out for a period of 72 hours (3 days). Results in the form of both animated maps and text output are displayed on a restricted access web browser, and information is updated each time the weather prediction model produces a new forecast (i.e., every 6 hours) (Pearce and Majorhazi 2003). More recently, MetService (Simmers 2005) developed a method for producing medium range forecasts of fire weather indices that showed skill as far as day 10, and the MetConnect system was expanded to also include forecasts of daily FWI values over this extended period. However, the anticipated ability of the forecasts to add situation-dependent probabilistic information was not found. Using a different approach, recent research at NIWA (Renwick et al. 2007) suggests that weather elements can be skilfully predicted in a probabilistic sense out to 10-12 days, and that such forecasts can indicate tendencies for the coming month with a modest amount of skill.

3.4 Two – four week prediction

A scheme has been developed that predicts the likely range of temperature (daily maximum and minimum, soil), average wind speed, daily rainfall and solar radiation at 70 sites across New Zealand, with rainfall and temperature at over 100 sites, from one day out to two weeks, with an extension that estimates temperate and rainfall for a month out. The basis of the scheme is a set of diagnostic or "downscaling"

[2] http://nrfa/fire.org.nz/fire_weather/niwa/index.htm

relationships between observed components of the large-scale circulation (pressure patterns, regional air temperatures, etc) and local daily climate variables at each station. The predictive component is supplied by a weather prediction model that forecasts the large scale circulation out to two weeks ahead. Predicted circulation indices are substituted for the observed values used to develop the downscaling relationships. Hence, assuming the forecast is correct, estimates are obtained of what the local weather would be in those circumstances.

Estimated variability in the forecasts comes from the use of an "ensemble" approach to the weather prediction problem. Here, the weather model is run several times (in this case, 11 times) for each day, with slightly modified starting states, thus capturing the effects of chaos in the atmospheric circulation. By using the downscaling relationships with each member of the ensemble, an estimate can be made of the most likely daily outcome, and the likely range of variability around that. The scheme is Skilful On A Day-By-Day Basis Out To About A Week, And Its Aggregated Qualitative indications (dry, very dry, warm, etc) are reliable during the second week. To go to monthly forecasts, the predictions for the first two weeks of the 30-day period are averaged and used to estimate the probability distribution of outcomes for the whole 30-day period. This approach shows most skill for daytime temperature, and is marginally skilful for rainfall.

A set of forecast values are calculated for each day of the two-week period, from the ensemble of weather model runs. For example, as shown in Figure 3, this gives information about the most likely outcome (the median forecast) and an estimate of the variability (the gray shading). As expected, due to chaotic effects in the weather, the width of the shading increases with increasing forecast interval.

The actual maximum temperatures are illustrated in blue in Figure 3. As is typical of such predictions, the estimates for the first few days are accurate (within a degree or so out to the end of the first week). Beyond that, we should not expect the exact daily sequence to be correctly predicted (again due to "chaos") but the trend should be properly indicated. As shown below, the forecast picks that the second week will be cooler than normal, but shows the coolest day to be the 27th, though the observations show the 26th as the coolest.

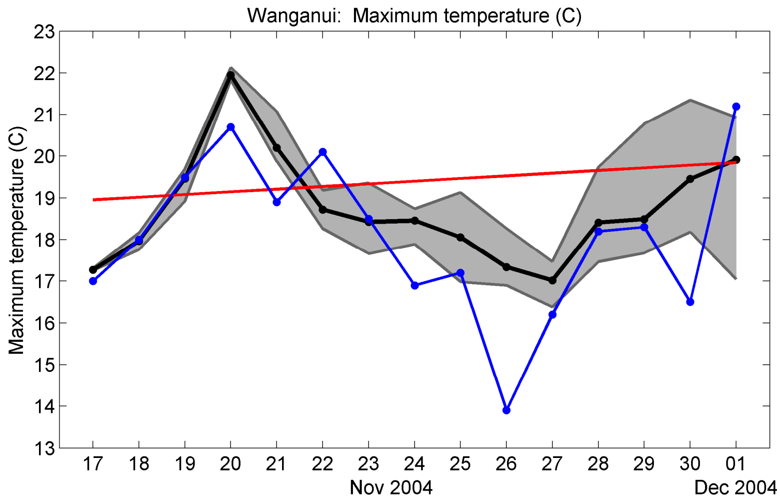

Figure 3: Example two-week maximum temperature forecasts for Wanganui, from the testing period in 2004. The day of the month is indicated along the bottom axis and the temperature is indicated up the vertical axis. The black line is the median daily forecast from the ensembles, and the gray shading shows the inter-quartile range of the forecasts (the interval within which the middle 50% of the forecast values lie). The red line shows the normal value for the time of year, and the blue line shows the actual outcomes.

Inherent uncertainties in the climate system mean that predictions can be quantitative and categorical only for the first few days. Beyond that, predictions must become more probabilistic and qualitative, but must reliably indicate trends. The system developed here appears to exhibit good reliability out to week two, and beyond that shows skill in estimating climate anomalies for the month.

4. Methodology

The broad aim of the current research is to investigate how much weekly to monthly-scale fire danger forecasts could be improved, using such information. In effect, the research described here provides a longer-term context for short-term (1-2 days) FWI forecasts provided to NRFA by MetService of New Zealand by providing a forecast that bridges the gap between a pure weather forecast of day to day changes over the coming few days and a climate forecast of changing risks over the coming months.

As noted previously, the key steps in this study included:

1. Relating Fire Weather Index (FWI) System components from observed and simulated daily climate information to regional scale weather variables predicted by the US National Weather Service global forecasting model, for sites in Northland and Canterbury;

2. Developing multivariate relationships between FWI and its components and available weather/climate variables;

3. Testing the derived relationships with real-time forecasts model output;

4. Presentation of the results and assessment of the feasibility of implementation of a FWI prediction scheme for key regions in New Zealand.

4.1 Relating FWI components to observed simulated daily climate information

The performance of the prediction scheme in terms of rainfall forecasts for week two (days 8-14) was examined, and relationships between daily climate variables and FWI components analysed.

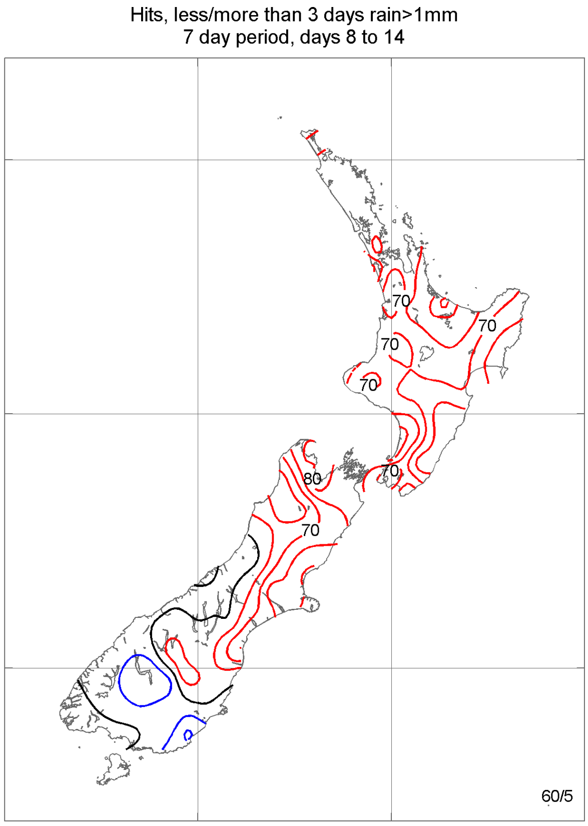

Figure 4: Percentage correct forecasts, for predicting whether or not at least half of week two will be wet. The contours represent the percent frequency of correct forecasts. The black line is 60%, blue is less than 60%, red is greater than 60% and the contour interval is 5%. Results based on a 20-month trial from August 2004 to March 2006.

For the second week of the forecast, the prediction system does a good job of discriminating wet periods from non-wet periods, though its ability to predict amounts of rainfall becomes very limited by the end of the first week and shows no skill for the second week. However, there is skill in a qualitative sense in terms of the number of days of rain in a week. Figure 4 illustrates the forecast performance for week two, in terms of the percentage of occasions where the model correctly predicted the occurrence of rain for at least half the week (4-7 days wet vs 0-3 days wet). The forecasts were correct around 70% of the time in most places. Comparisons were made of FWI components at fire weather stations and daily climate values at climate stations (as predicted by the two-week forecasting scheme). Indications are that combinations of up to three daily climate variables (e.g. maximum temperature, rainfall, daily wind run) capture over half of the variability in most of the FWI components.

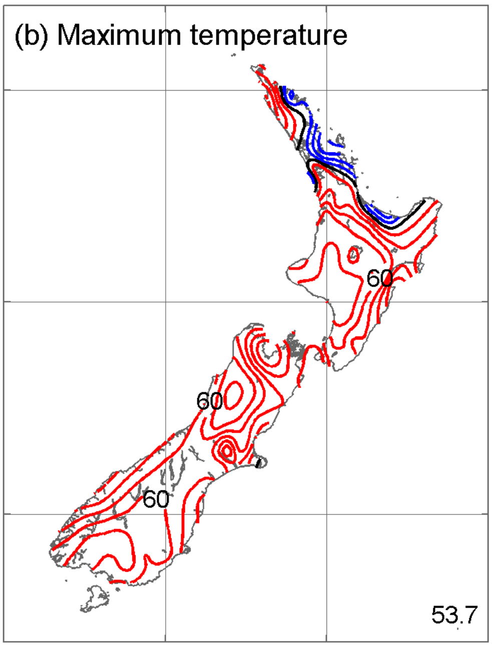

Figure 5. Amount of variance explained (compared to a forecast of climatology) by forecasts of maximum temperature averaged over days 3-7. The black contour is 50%, red is greater than 50% and blue is less than 50%. The contour interval is 5%. The average across all sites is printed in the bottom right corner.

Given the available resources for this component of the research project, analysis was limited to a set of sites in two key areas, Northland and Canterbury. These two regions were selected because conditions leading to high fire risk were quite different. In the former case (Northland) higher fire risk occurred with anticyclones producing southerly flow (Heydenruch and Salinger, 2002).For Canterbury high fire risk occurred with strong westerly or north westerly flow. For each Fire Service network station, the closest NIWA climate station was selected. These stations and their locations are listed in Table 1.

The data set of the predictands is from the NZ Fire Service's archive. The data includes five meteorological variables (temperature, relative humidity, wind speed, wind direction and precipitation); the fire Weather Index (FWI) System components, including three fuel moisture codes (Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC) and Drought Code (DC)) and three fire behaviour indexes (Initial Spread Index (ISI), Build Up Index (BUI) and the Fire Weather Index (FWI) itself). (Van Wagner 1987; also see Fig. 1b); and the Daily Severity Rating (DSR), a measure of daily fire weather severity calculated from the FWI value suitable for averaging (Harvey *et al*. 1986).

Table 1. Name of location of selected Northland and Canterbury NZ Fire Service network stations and their closest NIWA stations

NZ Fire Service network station	NZ map grid x	NZ map grid y	Closest NIWA station	NZ map grid x	NZ map grid y
Aupori_Peninsula	2513200	6722800	A53127	2534726	6674248
Pouto	2605200	6549200	A53987	2587603	6585365
Waitangi_Forest	2600500	6657300	A53191	2595185	6668397
Whangarei_Aero	2634261	6603070	A54737	2634016	6602816
Ashley	2409400	5700450	H31883	2413039	5712095
Balmoral	2489700	5816100	H22783	2497415	5826546
Bottle_Lake	2484300	5748700	H32451	2472572	5746132
Darfield	2441300	5745650	H32416	2441273	5745553
Snowdon	2402600	5748100	H31594	2424819	5741811

Two main data sets of predictors were analysed. The first data set comprises the large-scale meteorological variables analysed ("observed") through the "reanalysis project" carried out at the US National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Science (NCAR) (Kalnay et al. 1996) for the New Zealand region (30-50°S and 160°E-170°W). These included:

1. The first five principal components ("patterns") of the regional 1000 hPa height

field (1000p1 – 1000p5);

2. The first five principal components or regional temperature field at the 850hPa level (T850p1 – T850p5);

3. The regional mean of the westerly wind component (U1000);

4. The regional mean of the southerly wind component (V1000);

5. Wind speed at 1000 hPa (F1000);

6. Temperature at 850hPa (T850),

7. Regional mean vorticity (Vort).

The second data set comprises observed daily climate variables at the closest NIWA stations including precipitation (Rain), maximum temperature (Tmax), minimum temperature (Tmin), solar radiation (Solar), earth temperature (Tearth) and wind run (WindR).

5. Results

Correlations between the predictand data set and the three predictor data sets are listed in Tables 2-10 for each New Zealand Fire Service network station respectively.

5.1 Northland

Four stations were examined for Northland: Aupouri Peninsula, Pouto, Waitangi Forest and Whangarei Airport. These were selected to give a spread over Northland and proximity to NIWA stations.

Results for the Aupouri Peninsula (Table 2a) show that the regional vorticity data set (a proxy for storminess, vertical motion and rainfall) was the best predictor for FFMC and FWI. Using meteorological variables (Table 2b) generally only significant relationships existed for the prediction of higher FFMC with lack of rainfall (Rain), higher minimum temperature (Tmin) and increased solar radiation (Solar). For ISI and DSR significant relationships were found with wind run (WindR).

Similarly at Pouto (Table 3a) regional vorticity again was the only significant NCEP predictor for FFMC, FWI and ISI. Using meteorological variables at the nearest climate station (Table 3b) again only significant relationships existed with the FFMC predictand with lack of rainfall, higher minimum temperature and increased solar radiation. There was also a significant relationship between ISI and wind run.

At Waitangi Forest again regional vorticity was important for FFMC, ISI and FWI, although southerly wind strength (V1000) was also important (Table 4a). The negative of the third principal component of 1000hPa height represents high pressure ridges over Northland, and this showed relationships with DMC, DC and BUI. FFMC was the only predictand with significant relationships with weather variables (Table 4b) including rainfall, minimum temperature and solar radiation.

Table 2. Correlation coefficients of fire risk indexes with climate variables for Aupouri Peninsula.

(a) With NCEP reanalysis data

	temp	rel_hu	w_spe	w_dir	prec	ffmc	dmc	dc	isi	bui	fwi	dsr
1000p1	0.08	0.03	0.15	**-0.49**	-0.12	0.09	0.15	0.10	0.25	0.15	0.25	0.24
1000p2	-0.24	-0.27	0.03	0.22	-0.19	0.28	0.04	0.01	0.17	0.03	0.13	0.06
1000p3	-0.25	0.04	0.14	0.00	0.16	-0.17	-0.31	-0.28	-0.03	**-0.33**	-0.16	-0.05
1000p4	-0.08	-0.24	-0.09	0.06	-0.15	0.25	-0.01	-0.06	0.08	-0.01	0.05	0.00
1000p5	0.06	-0.02	-0.06	-0.19	-0.14	0.20	0.07	-0.03	0.09	0.07	0.10	0.06
T850p1	**0.34**	0.21	0.00	-0.24	0.04	-0.15	0.00	0.04	-0.02	0.00	0.01	0.05
T850p2	0.01	0.08	-0.13	**0.32**	0.15	-0.22	-0.11	-0.05	-0.26	-0.11	-0.24	-0.19
T850p3	0.17	0.13	-0.10	-0.01	-0.08	0.06	0.12	0.12	0.01	0.13	0.06	0.04
T850p4	-0.15	-0.13	0.08	0.11	0.07	-0.03	-0.16	-0.10	0.05	-0.16	-0.03	0.00
T850p5	0.12	-0.15	-0.01	0.04	-0.14	0.18	0.10	0.09	0.08	0.10	0.10	0.04
U1000	0.12	-0.03	-0.22	**0.49**	0.01	0.01	0.01	0.01	-0.21	0.01	-0.16	-0.20
V1000	-0.28	**-0.36**	-0.06	**0.35**	-0.11	0.22	-0.11	-0.08	0.04	-0.12	-0.03	-0.07
F1000	-0.08	0.12	**0.64**	0.03	0.18	-0.17	-0.05	0.02	0.23	-0.04	0.16	0.23
T850	**0.33**	**0.33**	-0.15	-0.05	0.07	-0.19	0.03	0.07	-0.14	0.03	-0.08	-0.04
Vort	0.17	-0.21	0.01	-0.18	**-0.40**	**0.41**	0.21	0.07	**0.32**	0.22	**0.34**	0.26

(b) With observed daily climate data at the nearest climate station

	temp	rel_hu	w_spe	w_dir	prec	ffmc	dmc	dc	isi	bui	fwi	dsr
Rain	-0.02	**0.32**	0.01	0.02	**0.34**	**-0.41**	-0.09	-0.02	-0.20	-0.08	-0.19	-0.12
Tmax	**0.60**	0.13	-0.20	**-0.41**	-0.21	0.16	0.19	**0.42**	-0.04	0.22	0.06	0.01
Tmin	**0.37**	**0.43**	0.14	-0.09	0.21	**-0.41**	-0.10	0.22	-0.16	-0.07	-0.15	-0.05
Solar	0.00	**-0.44**	-0.08	0.07	-0.28	0.44	0.02	-0.12	0.18	0.01	0.15	0.05
Tearth	**0.51**	**0.38**	-0.09	-0.20	0.01	-0.11	0.16	0.27	-0.08	0.18	0.01	0.02
WindR	0.01	0.10	**0.66**	0.15	0.16	-0.08	0.11	-0.07	**0.31**	0.10	0.28	**0.33**

Labels for NCEP climate indices (in rows):
1000p*i* = *i*th principal component of the NZ 1000 hPa height field**,** T850p*i* = *i*th principal component of 850 hPa temperature in the New Zealand region, U1000 = component of westerly wind direction, V1000 = component of westerly wind direction, F1000 = wind speed at 1000 hPa, and Vort = Vorticity.
Labels for observed climate indices (in rows):
Rain = precipitation, Tmax = maximum temperature, Tmin = minimum temperature, Solar = solar radiation, Tearth = Earth temperature, and WindR = daily wind run.
Labels for fire risk indices (in columns):
rel_hu = relative humidity, w_spe = wind speed, w-dir = wind direction, prec = precipitation, ffmc = fine fuel moisture cond, dmc = Duff Moisture Code, dc - Drought Code, isi - Initial Spread Index, bui - Buildup Index, fwi - Fire Weather Index, and dsr – Daily Severity Rating.

Table 3. Correlation coefficients of fire risk indexes with climate variables for Pouto

(a) With NCEP reanalysis data

	temp	rel_hu	w_spe	w_dir	prec	ffmc	dmc	dc	isi	bui	fwi	dsr
1000p1	-0.01	-0.22	-0.17	**-0.45**	-0.12	0.24	0.16	0.03	0.16	0.15	0.18	0.10
1000p2	0.04	-0.21	0.12	0.25	-0.12	0.16	0.06	0.02	0.18	0.05	0.14	0.14
1000p3	-0.02	0.16	-0.01	-0.20	0.12	-0.19	-0.22	-0.22	-0.13	-0.24	-0.19	-0.11
1000p4	-0.03	-0.13	-0.07	0.11	-0.12	0.19	-0.04	0.00	0.03	-0.04	-0.02	-0.04
1000p5	0.00	-0.16	-0.16	-0.16	-0.19	0.24	0.07	0.01	0.03	0.07	0.04	0.00
T850p1	-0.01	0.21	-0.14	-0.23	0.01	-0.08	0.00	0.06	-0.09	0.02	-0.04	-0.06
T850p2	0.01	0.26	0.13	**0.31**	0.18	-0.27	-0.16	-0.09	-0.14	-0.16	-0.15	-0.07
T850p3	-0.04	0.14	-0.03	0.05	-0.04	0.01	0.05	0.08	-0.02	0.06	0.00	0.02
T850p4	0.03	0.02	0.03	-0.01	0.08	-0.14	-0.18	-0.07	-0.15	-0.17	-0.19	-0.14
T850p5	0.00	-0.14	0.00	0.15	-0.14	0.16	0.12	0.09	0.15	0.13	0.16	0.13
U1000	0.05	0.16	0.22	**0.62**	0.09	-0.16	-0.04	0.05	-0.06	-0.03	-0.06	-0.02
V1000	-0.03	-0.25	0.06	**0.33**	-0.15	0.21	-0.03	-0.02	0.11	-0.04	0.05	0.04
F1000	-0.02	0.15	**0.50**	-0.18	0.10	-0.13	-0.05	-0.12	0.22	-0.07	0.13	0.17
T850	-0.02	**0.40**	-0.09	0.00	0.06	-0.18	-0.03	0.08	-0.15	0.00	-0.10	-0.07
Vort	0.07	**-0.32**	-0.05	-0.15	**-0.34**	**0.43**	0.29	0.10	**0.30**	0.28	**0.33**	0.23

(b) With observed daily climate data at the nearest climate station

	temp	rel_hu	w_spe	w_dir	prec	ffmc	dmc	dc	isi	bui	fwi	dsr
Rain	0.01	**0.35**	-0.05	-0.13	0.27	**-0.42**	-0.12	-0.05	-0.21	-0.12	-0.19	-0.11
Tmax	-0.02	-0.04	-0.24	-0.26	-0.15	0.16	0.29	**0.40**	0.06	**0.33**	0.18	0.11
Tmin	0.00	**0.46**	0.15	-0.12	0.19	**-0.39**	-0.09	0.15	-0.18	-0.06	-0.15	-0.08
Solar	-0.01	**-0.55**	0.04	**0.34**	-0.18	**0.42**	0.10	-0.13	0.23	0.08	0.20	0.10
Tearth	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
WindR	-0.08	0.08	**0.68**	-0.01	0.02	-0.04	0.02	-0.01	**0.37**	0.00	0.26	0.29

Table 4: Similar to Table 3, but for Waitangi Forest

(a) With NCEP reanalysis data

	temp	rel_hu	w_spe	w_dir	prec	ffmc	dmc	dc	isi	bui	fwi	dsr
1000p1	-0.17	-0.02	-0.03	**-0.39**	-0.08	0.08	0.14	0.10	-0.01	0.14	0.06	0.00
1000p2	-0.09	-0.38	-0.04	**0.36**	-0.15	0.22	0.07	-0.04	0.22	0.05	0.18	0.18
1000p3	-0.24	0.22	0.07	-0.04	0.20	-0.25	**-0.35**	**-0.35**	-0.19	**-0.37**	-0.28	-0.21
1000p4	0.02	-0.24	-0.18	0.06	-0.07	0.16	-0.11	-0.10	0.03	-0.11	-0.04	-0.05
1000p5	0.05	-0.11	-0.05	-0.23	-0.19	0.22	0.09	0.03	0.09	0.08	0.10	0.03
T850p1	0.25	0.25	-0.04	**-0.32**	0.04	-0.13	0.00	0.07	-0.13	0.01	-0.08	-0.11
T850p2	0.19	0.13	0.02	0.28	0.10	-0.14	-0.09	-0.06	-0.05	-0.09	-0.07	-0.03
T850p3	0.23	-0.02	-0.13	0.06	-0.06	0.06	0.13	0.02	0.09	0.10	0.11	0.12
T850p4	-0.15	0.01	-0.01	0.04	0.14	-0.15	-0.13	-0.14	-0.08	-0.14	-0.11	-0.09
T850p5	0.16	-0.19	-0.03	0.07	-0.14	0.21	0.13	0.15	0.16	0.14	0.17	0.12
U1000	**0.34**	-0.15	0.02	**0.46**	-0.04	0.10	0.12	0.16	0.15	0.13	0.15	0.17
V1000	0.03	**-0.48**	-0.16	**0.34**	-0.14	**0.30**	-0.04	-0.12	0.20	-0.06	0.11	0.10
F1000	-0.26	0.20	**0.57**	0.14	0.17	-0.19	-0.11	-0.10	0.15	-0.12	0.06	0.12
T850	**0.38**	0.29	-0.12	-0.06	0.06	-0.18	0.02	0.03	-0.11	0.02	-0.07	-0.04
Vort	0.09	-0.28	0.11	-0.23	**-0.40**	**0.43**	0.22	0.14	**0.31**	0.23	**0.31**	0.22

(b) With observed daily climate data at the nearest climate station

	temp	rel_hu	w_spe	w_dir	prec	ffmc	dmc	dc	isi	bui	fwi	dsr
Rain	-0.23	**0.44**	0.11	-0.09	**0.33**	**-0.47**	-0.10	-0.04	-0.23	-0.10	-0.20	-0.12
Tmax	**0.75**	-0.21	-0.19	0.11	-0.20	0.26	0.25	**0.34**	0.14	0.28	0.22	0.17
Tmin	0.17	**0.55**	0.13	-0.14	0.20	**-0.40**	-0.02	0.19	-0.22	0.01	-0.16	-0.09
Solar	**0.40**	**-0.72**	-0.13	0.17	-0.29	**0.54**	0.13	-0.04	**0.37**	0.11	**0.30**	0.21
Tearth	**0.44**	0.17	-0.01	-0.18	-0.06	-0.01	**0.30**	**0.36**	0.08	**0.32**	0.19	0.19
WindR	-0.10	0.14	**0.51**	0.01	0.10	-0.09	-0.09	-0.22	0.15	-0.12	0.05	0.07

Table 5: Similar to Table 2, but for Whangarei Aero

(a) With NCEP reanalysis data

	temp	rel_hu	w_spe	w_dir	prec	ffmc	dmc	dc	isi	bui	fwi	dsr
1000p1	-0.12	0.08	0.09	**-0.51**	-0.05	0.07	0.16	0.17	0.05	0.17	0.11	0.05
1000p2	-0.18	**-0.31**	0.15	0.21	-0.14	0.23	0.08	-0.01	**0.30**	0.06	0.23	0.21
1000p3	-0.16	0.22	0.20	-0.16	0.21	-0.23	**-0.34**	**-0.33**	-0.14	**-0.35**	-0.25	-0.20
1000p4	-0.06	-0.21	-0.04	0.04	-0.07	0.16	-0.05	-0.06	0.10	-0.05	0.04	0.01
1000p5	0.04	-0.16	-0.12	-0.14	-0.21	0.27	0.09	0.04	0.15	0.09	0.13	0.04
T850p1	0.28	0.24	-0.07	-0.23	0.05	-0.08	-0.03	0.03	-0.11	-0.01	-0.07	-0.10
T850p2	0.14	0.09	-0.08	**0.36**	0.10	-0.17	-0.12	-0.12	-0.13	-0.12	-0.14	-0.07
T850p3	0.15	0.01	-0.08	0.01	-0.08	0.09	0.18	0.10	0.13	0.16	0.18	0.17
T850p4	-0.19	0.05	0.15	-0.04	0.10	-0.13	-0.18	-0.15	-0.07	-0.19	-0.14	-0.11
T850p5	0.10	-0.20	0.00	0.11	-0.15	0.20	0.08	0.07	0.18	0.09	0.16	0.12
U1000	0.26	-0.23	-0.14	**0.64**	-0.04	0.07	0.09	0.09	0.06	0.09	0.09	0.11
V1000	-0.16	**-0.40**	0.11	0.24	-0.13	0.27	-0.02	-0.11	0.28	-0.05	0.16	0.15
F1000	-0.16	0.24	**0.59**	-0.01	0.19	-0.21	-0.15	-0.13	0.04	-0.15	-0.04	0.02
T850	**0.36**	0.28	-0.18	0.03	0.05	-0.13	0.05	0.07	-0.09	0.05	-0.02	0.00
Vort	0.15	**-0.35**	-0.03	-0.13	**-0.41**	**0.45**	0.23	0.18	**0.35**	0.24	**0.34**	0.23

(b) With observed daily climate data at the nearest climate station

	temp	rel_hu	w_spe	w_dir	prec	ffmc	dmc	dc	isi	bui	fwi	dsr
Rain	-0.12	**0.41**	0.07	-0.07	**0.37**	**-0.45**	-0.14	-0.07	-0.27	-0.13	-0.23	-0.15
Tmax	**0.69**	-0.22	**-0.35**	0.22	-0.17	0.25	**0.31**	**0.40**	0.09	**0.35**	0.24	0.19
Tmin	0.25	**0.51**	0.09	-0.14	0.17	**-0.35**	-0.04	0.18	-0.26	0.00	-0.17	-0.09
Solar	0.21	**-0.72**	-0.06	0.16	**-0.31**	**0.54**	0.12	-0.07	**0.39**	0.09	**0.31**	0.20
Tearth	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
WindR	-0.20	0.15	**0.74**	-0.09	0.08	-0.11	-0.12	-0.14	0.21	-0.14	0.08	0.14

Finally at Whangarei Aero (Table 5a) vorticity was the key regional predictor which had high correlations with FFMC and FWI, although high pressure ridges over Northland are important for some fuel codes (DMC, DC and BUI). Local meteorological predictors Table 5b) again were rainfall, minimum temperature and solar radiation for FFMC and FWI.

Table 6 Aupouri Peninsula - A53127. Multiple regression analysis between components of the FWI system and regional climate indices, and explained variance.

	Prediction equation	R-Squared
FFMC	+Vort+H1000pc2+H1000pc4	0.31
DMC	-H1000pc3+H1000pc1+Vort	0.13
DC	-H1000pc3+H1000pc1+F1000	0.10
ISI	+Vort+F1000+H1000pc2-T850pc2	0.29
BUI	-H1000pc3+H1000pc1+Vort	0.14
FWI	+Vort+F1000+H1000pc1+H1000pc2	0.24
DSR	+Vort+F1000+H1000pc1+H1000pc2	0.20

From multiple regression analyses, at Aupouri Peninsula FFMC, ISI and FWI are best predicted of the various fuel moisture and fire weather indices (Table 6). Positive regional mean vorticity and southerly airflow pattern(H1000pc2), ie more anticyclonic conditions are important here.

Table 7 Similar to Table 6, but for Pouto - A53987.

	Prediction equation	R-squared
FFMC	+Vort+V1000-H1000pc3	0.27
DMC	+Vort-H1000pc3-T850pc2	0.13
DC	-H1000pc3-T850pc2	0.06
ISI	+Vort+F1000+H1000pc2	0.21
BUI	+Vort-H1000pc3-T850pc2	0.13
FWI	+Vort+H1000pc2+F1000	0.17
DSR	+Vort+F1000+H1000pc2	0.12

At Pouto (Table 7) only FFMC is reasonably predicted with positive vorticity and southerly wind fields and ridges (V1000 and H1000pc1 and H1000pc2) over Northland being the most important.

Table 8 Similar to Table 6, but for Waitangi Forest - A53191.

	Prediction equation	R-Squared
FFMC	+Vort+V1000-H1000pc3	0.36
DMC	-H1000pc3+H1000pc1+U1000+Vort	0.21
DC	-H1000pc3+H1000pc1+U1000	0.18
ISI	+Vort+H1000pc2+F1000	0.21
BUI	-H1000pc3+H1000pc1+U1000	0.21
FWI	+Vort+H1000pc2-H1000pc3+F1000	0.24
DSR	+Vort+H1000pc2-H1000pc3+F1000	0.17

Again FFMC was the best predictand for Waitangi Forest (Table 8) again with vorticity, a southerly wind field (V1000) and anticyclonic conditions (H1000pc1and H1000pc2), although FWI was reasonably predicted (Table 8) with wind speed (F1000) also being important.

Table 9 Similar to Table 6, but for Whangarei Aero - A54737.

	Prediction equation	R-Squared
FFMC	+Vort+V1000-H1000pc3	0.33
DMC	-H1000pc3+Vort+H1000pc1+U1000	0.18
DC	-H1000pc3+H1000pc1+U1000	0.17
ISI	+Vort+H1000pc2+V1000+F1000	0.27
BUI	-H1000pc3+H1000pc1+U1000	0.18
FWI	+Vort+H1000pc2-H1000pc3	0.22
DSR	+Vort+H1000pc2-H1000pc3+F1000	0.14

Anticyclonic conditions (H1000pc3) with southerly winds (V1000) were the most important predictors for FFMC, which is best predicted of the predictands at Whangarei Airport (Table 9). ISI was the next best predicted.

Summary: Strongest relationships were found for Fine Fuel Moisture Code (FFMC) and the Fire Weather Index (FWI) value itself with analysed regional vorticity (a proxy for storminess, vertical motion and rainfall) at all stations, and FFMC with rainfall, minimum temperature and solar radiation at the nearest climate station. For Northland, anticyclonic conditions coupled with enhanced southerly winds are associated with higher FFMC and FWI values. The variance accounted for in regressions on FFMC and FWI typically ranged from 15 to 25%, for contemporary relationships (today's FWI System values from today's weather).

5.2 Canterbury

Five stations were examined for the Canterbury region: Ashley Forest, Balmoral Forest, Bottle Lake, Darfield and Snowdon. These were selected to give a geographic spread over Canterbury and proximity to NIWA stations.

At Ashley Forest (Table 10) FFMC, ISI, FWI and DSR were all reasonably correlated with higher temperatures (T850p1 and, to a lesser extent T850) and stronger westerly winds (U1000) across the region. Locally higher maximum temperatures, earth temperatures (and solar radiation in the case of FFMC) were correlated with all these fire weather indices as well as BUI.

Balmoral Forest correlations (Table 11) for ISU, FWI and DSR were also highest with stronger westerly winds (U1000) and higher temperatures regionally (T850p1 and T850). Using local data these predictands together with BUI and FFMC had significant relationships with higher maximum, minimum and earth temperatures locally, and higher wind run.

Of the regional fields, only the incidence of westerly winds (U1000) was an important predictor at Bottle Lake (Table 12) giving some correlation for ISI, FWI and DSR. Locally higher maximum and earth temperatures were the most important for FWI and

DSR.

At Darfield (Table 13) FWI and DSR showed the highest correlations with regional westerly flow (U1000), although temperature (T850) was important for FFMC. Of the local meteorological variables, higher maximum temperatures showed the best associations.

Similarly, regional westerly winds (U1000) were important for predicting FWI and DSR at Snowdon (Table 14). At this site only maximum temperatures locally were important, with good associations with all fire weather indices (FFMC, DMC, DC, ISI, BUI, FWI and DSR.

Table 10: Similar to Table 2, but for Ashley Forest.

(a) With NCEP reanalysis data

	temp	rel_hu	w_spe	w_dir	prec	ffmc	dmc	dc	isi	bui	fwi	dsr
1000p1	0.16	-0.02	-0.13	-0.20	-0.18	0.14	0.10	0.13	-0.04	0.12	0.01	-0.05
1000p2	**-0.45**	0.18	-0.04	0.11	0.07	-0.25	-0.22	-0.11	-0.22	-0.22	-0.26	-0.20
1000p3	**-0.40**	**0.45**	-0.22	-0.13	0.20	**-0.32**	-0.28	-0.10	**-0.42**	-0.26	**-0.42**	**-0.38**
1000p4	0.25	-0.27	0.08	-0.04	-0.15	0.19	-0.01	-0.07	0.13	-0.02	0.11	0.10
1000p5	0.10	-0.09	-0.14	-0.28	-0.14	0.13	0.01	0.01	-0.01	0.01	0.00	0.01
T850p1	**0.56**	-0.18	0.07	-0.03	-0.12	0.33	**0.31**	0.24	**0.34**	**0.32**	**0.39**	**0.31**
T850p2	-0.28	0.13	0.19	0.29	0.18	-0.18	0.01	-0.06	0.06	-0.01	0.04	0.08
T850p3	0.01	-0.08	0.00	-0.05	-0.11	0.15	0.17	0.16	0.07	0.18	0.09	0.07
T850p4	-0.28	0.22	-0.16	-0.18	0.13	-0.26	-0.19	-0.05	-0.28	-0.18	-0.29	-0.23
T850p5	-0.09	0.05	0.00	0.09	0.05	-0.07	0.13	0.09	0.00	0.13	0.05	0.06
U1000	**0.43**	**-0.57**	0.23	0.14	-0.28	**0.38**	0.17	0.05	**0.45**	0.15	**0.40**	**0.36**
V1000	**-0.47**	0.25	0.10	**0.33**	0.24	**-0.34**	-0.16	-0.07	-0.17	-0.16	-0.20	-0.13
F1000	-0.16	0.03	0.26	0.10	**0.30**	-0.20	-0.10	-0.10	0.05	-0.11	-0.01	0.05
T850	**0.66**	-0.25	-0.03	-0.13	-0.21	**0.42**	0.26	0.19	0.29	0.26	**0.33**	0.23
Vort	-0.18	0.06	-0.16	-0.16	-0.06	-0.09	-0.06	-0.01	-0.09	-0.05	-0.10	-0.06

(b) With observed daily climate data at the nearest climate station

	temp	rel_hu	w_spe	w_dir	prec	ffmc	dmc	dc	isi	bui	fwi	dsr
Rain	-0.18	0.21	-0.01	0.10	0.22	-0.18	0.00	-0.02	-0.08	0.00	-0.08	-0.04
Tmax	**0.90**	**-0.68**	0.14	-0.03	**-0.33**	**0.60**	**0.39**	0.27	**0.56**	**0.40**	**0.59**	**0.47**
Tmin	**0.34**	0.04	0.04	0.08	-0.02	0.14	0.27	0.19	0.22	0.27	0.28	0.25
Solar	**0.43**	**-0.53**	0.17	-0.12	-0.26	**0.37**	0.10	0.01	0.27	0.08	0.25	0.18
Tearth	**0.42**	-0.12	0.06	0.07	-0.17	**0.38**	**0.52**	**0.40**	**0.36**	**0.53**	**0.47**	**0.39**
WindR	0.24	-0.27	0.26	-0.17	-0.04	0.18	0.16	0.05	0.25	0.15	0.25	0.26

Table 11: Similar to Table 2, but for Balmoral Forest.

(a) With NCEP reanalysis data

	temp	rel_hu	w_spe	w_dir	prec	ffmc	dmc	dc	isi	bui	fwi	dsr
1000p1	0.21	-0.08	-0.26	-0.24	-0.18	0.18	0.13	0.12	-0.02	0.13	0.03	0.00
1000p2	**-0.43**	0.15	-0.02	-0.11	0.03	-0.18	-0.22	-0.06	-0.17	-0.20	-0.24	-0.19
1000p3	**-0.36**	**0.43**	**-0.40**	**-0.35**	0.12	-0.29	-0.15	-0.11	**-0.45**	-0.14	**-0.44**	**-0.42**
1000p4	0.20	-0.25	0.03	0.03	-0.13	0.16	-0.02	-0.06	0.12	-0.03	0.12	0.09
1000p5	0.10	-0.11	-0.17	-0.14	-0.15	0.13	0.03	0.01	-0.01	0.03	0.01	0.00
T850p1	**0.59**	-0.22	0.05	0.07	-0.09	0.28	**0.31**	0.18	**0.32**	**0.31**	**0.39**	**0.35**
T850p2	-0.29	0.19	0.27	0.24	0.19	-0.19	-0.03	-0.06	0.01	-0.03	-0.01	0.02
T850p3	0.00	-0.09	0.05	-0.01	-0.11	0.20	0.16	0.16	0.09	0.17	0.13	0.10
T850p4	**-0.30**	0.17	-0.21	-0.23	0.05	-0.16	-0.14	-0.02	-0.28	-0.12	-0.29	-0.27
T850p5	-0.08	0.05	0.04	0.01	0.04	-0.08	0.08	0.08	-0.02	0.08	0.03	0.04
U1000	**0.37**	**-0.48**	**0.51**	**0.51**	-0.12	**0.30**	0.07	0.03	**0.46**	0.06	**0.43**	**0.40**
V1000	**-0.40**	0.16	0.16	0.02	0.17	-0.25	-0.17	-0.05	-0.09	-0.15	-0.15	-0.10
F1000	-0.22	0.16	**0.31**	0.18	0.15	-0.18	-0.04	-0.05	0.00	-0.05	-0.03	0.00
T850	**0.70**	**-0.30**	-0.03	0.02	-0.16	**0.37**	0.27	0.16	**0.35**	0.27	**0.40**	**0.34**
Vort	-0.01	-0.19	-0.01	-0.04	-0.21	0.13	0.03	0.01	0.08	0.02	0.06	0.08

(b) With observed daily climate data at the nearest climate station

	temp	rel_hu	w_spe	w_dir	prec	ffmc	dmc	dc	isi	bui	fwi	dsr
Rain	-0.21	**0.32**	-0.09	-0.01	**0.44**	**-0.36**	-0.08	-0.07	-0.16	-0.08	-0.18	-0.13
Tmax	**0.92**	**-0.67**	0.15	0.16	-0.31	**0.59**	**0.37**	0.29	**0.52**	**0.38**	**0.61**	**0.52**
Tmin	0.15	0.19	0.13	0.15	0.05	-0.01	0.27	0.16	0.08	0.26	0.17	0.17
Solar	**0.51**	**-0.71**	0.13	0.07	-0.28	**0.50**	0.14	-0.18	**0.40**	0.08	**0.42**	**0.36**
Tearth	**0.46**	-0.16	0.17	0.12	-0.18	**0.34**	**0.59**	**0.41**	**0.36**	**0.59**	**0.53**	**0.47**
WindR	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Table 12: Similar to Table 2, but for Bottle Lake.

(a) With NCEP reanalysis data

	temp	rel_hu	w_spe	w_dir	prec	ffmc	dmc	dc	isi	bui	fwi	dsr
1000p1	0.06	0.03	0.00	-0.22	-0.20	0.19	0.11	0.10	0.03	0.12	0.07	0.00
1000p2	**-0.40**	-0.03	0.07	0.15	0.11	-0.14	-0.24	-0.11	-0.19	-0.23	-0.23	-0.22
1000p3	**-0.39**	**0.36**	0.10	-0.03	0.14	-0.25	-0.20	-0.14	**-0.35**	-0.19	**-0.32**	**-0.32**
1000p4	0.18	-0.18	0.07	-0.13	-0.14	0.17	-0.04	-0.07	0.11	-0.04	0.07	0.05
1000p5	0.01	0.00	-0.01	-0.25	-0.16	0.10	0.01	0.02	0.03	0.01	0.04	0.02
T850p1	**0.50**	0.02	-0.07	-0.12	-0.14	0.21	0.26	0.22	0.26	0.27	**0.30**	0.26
T850p2	-0.07	-0.04	0.00	**0.32**	0.19	-0.15	0.05	-0.04	0.06	0.03	0.05	0.11
T850p3	-0.02	-0.06	-0.06	-0.09	-0.11	0.16	0.21	0.11	0.11	0.21	0.15	0.11
T850p4	**-0.32**	0.13	0.04	-0.07	0.07	-0.13	-0.11	-0.05	-0.24	-0.11	-0.21	-0.22
T850p5	-0.03	-0.04	-0.04	0.14	0.05	-0.05	0.07	0.11	-0.01	0.08	0.02	0.04
U1000	**0.48**	**-0.44**	-0.06	0.13	-0.10	0.24	0.11	0.05	**0.38**	0.10	**0.31**	**0.34**
V1000	**-0.32**	-0.02	0.13	0.29	0.25	-0.22	-0.18	-0.07	-0.15	-0.17	-0.17	-0.15
F1000	-0.04	-0.04	0.18	0.22	0.28	-0.20	-0.01	-0.01	0.05	-0.02	0.03	0.10
T850	**0.51**	0.04	-0.08	-0.25	-0.21	0.27	0.19	0.17	0.22	0.20	0.24	0.18
Vort	0.01	-0.22	0.00	-0.09	-0.19	0.13	0.01	0.03	0.06	0.01	0.06	0.04

(b) With observed daily climate data at the nearest climate station

	temp	rel_hu	w_spe	w_dir	prec	ffmc	dmc	dc	isi	bui	fwi	dsr
Rain	-0.17	0.26	0.03	0.08	0.29	-0.28	-0.08	-0.07	-0.17	-0.09	-0.17	-0.12
Tmax	**0.89**	**-0.54**	-0.15	-0.02	-0.26	**0.46**	**0.34**	0.27	**0.56**	**0.35**	**0.56**	**0.53**
Tmin	0.26	0.22	-0.05	0.00	-0.01	0.02	0.17	0.19	0.05	0.18	0.10	0.12
Solar	**0.37**	**-0.51**	0.24	-0.13	-0.23	**0.37**	0.04	-0.07	**0.36**	0.02	0.29	0.24
Tearth	**0.44**	0.01	-0.08	-0.05	-0.18	0.29	**0.39**	**0.36**	**0.33**	**0.41**	**0.40**	**0.37**
WindR	0.01	-0.02	**0.48**	-0.05	0.04	0.03	0.09	-0.04	0.23	0.07	0.20	0.21

Table 13: Similar to Table 2, but for Darfield.

(a) With NCEP reanalysis data

	temp	rel_hu	w_spe	w_dir	prec	ffmc	dmc	dc	isi	bui	fwi	dsr
1000p1	0.13	-0.02	-0.14	-0.25	-0.19	0.18	0.08	0.10	-0.08	0.10	-0.03	-0.08
1000p2	**-0.41**	0.08	-0.21	-0.14	0.12	-0.18	-0.20	-0.12	-0.20	-0.20	-0.26	-0.20
1000p3	**-0.42**	**0.44**	-0.29	**-0.32**	0.16	**-0.32**	**-0.33**	-0.15	**-0.42**	**-0.31**	**-0.45**	**-0.39**
1000p4	0.26	-0.27	0.15	-0.02	-0.19	0.24	-0.03	-0.07	0.13	-0.03	0.14	0.09
1000p5	0.10	-0.09	-0.04	-0.22	-0.16	0.14	0.04	0.02	0.00	0.04	0.03	0.01
T850p1	**0.52**	-0.10	0.15	0.08	-0.16	0.24	0.26	0.24	0.27	0.28	**0.32**	0.26
T850p2	-0.26	0.15	0.17	**0.33**	0.24	-0.23	0.00	-0.04	0.09	-0.01	0.04	0.11
T850p3	0.02	-0.11	-0.01	-0.02	-0.13	0.18	0.24	0.17	0.07	0.24	0.12	0.07
T850p4	-0.26	0.14	-0.27	-0.24	0.10	-0.20	-0.19	-0.07	-0.29	-0.19	**-0.31**	-0.26
T850p5	-0.08	0.04	-0.07	0.03	0.11	-0.07	0.12	0.11	-0.06	0.13	-0.01	-0.01
U1000	**0.47**	**-0.51**	**0.41**	**0.46**	-0.15	**0.35**	0.25	0.07	**0.50**	0.23	**0.50**	**0.46**
V1000	**-0.37**	0.10	-0.08	0.03	0.25	-0.25	-0.14	-0.09	-0.12	-0.14	-0.17	-0.10
F1000	-0.11	0.05	**0.33**	0.25	0.27	-0.20	-0.05	-0.03	0.16	-0.05	0.10	0.17
T850	**0.61**	-0.16	0.08	-0.03	-0.28	**0.35**	0.21	0.18	0.24	0.22	0.29	0.19
Vort	0.06	-0.23	-0.06	-0.08	-0.14	0.12	-0.01	0.02	0.05	-0.01	0.05	0.04

(b) With observed daily climate data at the nearest climate station

	temp	rel_hu	w_spe	w_dir	prec	ffmc	dmc	dc	isi	bui	fwi	dsr
Rain	-0.19	0.28	0.01	0.09	0.24	**-0.30**	-0.06	-0.04	-0.06	-0.06	-0.09	-0.03
Tmax	**0.90**	**-0.66**	0.19	0.15	**-0.36**	**0.61**	**0.44**	**0.36**	**0.45**	**0.45**	**0.56**	**0.41**
Tmin	**0.33**	0.10	0.13	0.19	-0.04	0.07	0.25	0.25	0.23	0.26	0.27	0.26
Solar	**0.52**	**-0.66**	0.15	-0.05	-0.29	**0.47**	0.14	-0.01	**0.30**	0.12	**0.33**	0.23
Tearth	**0.40**	-0.04	0.11	0.12	-0.20	0.29	**0.54**	**0.43**	**0.30**	**0.56**	**0.42**	**0.36**
WindR	0.17	-0.18	**0.57**	0.07	-0.03	0.15	0.08	0.00	**0.35**	0.07	**0.33**	**0.30**

Table 14: Similar to Table 2, but for Snowdon.

(a) With NCEP reanalysis data

	temp	rel_hu	w_spe	w_dir	prec	ffmc	dmc	dc	isi	bui	fwi	dsr
1000p1	0.22	-0.03	-0.20	-0.21	-0.21	0.18	0.17	0.14	-0.06	0.16	-0.02	-0.04
1000p2	**-0.34**	0.06	**-0.33**	-0.29	0.09	-0.18	-0.21	-0.14	-0.22	-0.21	-0.28	-0.23
1000p3	-0.20	**0.39**	**-0.51**	**-0.44**	0.15	-0.30	-0.22	-0.10	**-0.42**	-0.21	**-0.44**	**-0.37**
1000p4	0.25	-0.28	0.17	0.08	-0.17	0.21	-0.01	-0.07	0.16	-0.03	0.16	0.14
1000p5	0.19	-0.13	0.03	-0.05	-0.16	0.16	0.03	0.03	0.06	0.03	0.07	0.07
T850p1	**0.55**	-0.13	0.24	0.25	-0.14	**0.31**	**0.36**	0.26	0.28	**0.36**	**0.36**	0.29
T850p2	**-0.40**	0.22	0.17	0.18	0.27	-0.25	-0.08	-0.06	0.02	-0.08	-0.01	0.01
T850p3	-0.03	-0.09	0.11	0.02	-0.15	0.21	0.18	0.19	0.09	0.19	0.11	0.06
T850p4	-0.11	0.09	**-0.33**	-0.29	0.12	-0.18	-0.19	-0.09	-0.29	-0.18	**-0.32**	-0.27
T850p5	-0.05	0.04	-0.08	0.00	0.09	-0.07	0.11	0.10	-0.05	0.11	-0.01	0.00
U1000	0.22	**-0.45**	**0.64**	**0.58**	-0.13	**0.30**	0.12	0.03	**0.45**	0.12	**0.47**	**0.38**
V1000	**-0.33**	0.07	-0.25	-0.19	0.23	-0.24	-0.16	-0.11	-0.20	-0.16	-0.23	-0.19
F1000	-0.25	0.13	0.26	0.17	0.28	-0.22	-0.07	-0.04	0.12	-0.07	0.09	0.12
T850	**0.67**	-0.22	0.17	0.18	-0.27	**0.42**	**0.32**	0.21	0.26	**0.32**	**0.33**	0.25
Vort	0.10	-0.25	0.01	-0.01	-0.14	0.14	0.03	0.04	0.08	0.03	0.08	0.08

(c) With observed daily climate data at the nearest climate station

	temp	rel_hu	w_spe	w_dir	prec	ffmc	dmc	dc	isi	bui	fwi	dsr
Rain	-0.19	0.24	-0.02	0.00	0.25	-0.27	-0.08	-0.05	-0.03	-0.08	-0.05	-0.01
Tmax	**0.83**	**-0.67**	**0.44**	**0.44**	**-0.37**	**0.65**	**0.49**	**0.37**	**0.48**	**0.49**	**0.59**	**0.46**
Tmin	0.12	0.25	0.06	0.11	0.07	0.01	0.28	0.19	0.05	0.27	0.14	0.13
Solar	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Tearth	**0.35**	0.05	0.10	0.15	-0.11	0.28	**0.33**	0.04	0.14	**0.30**	0.20	0.14
WindR	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Multiple regression analysis results are given in Tables 15-19.

Table Similar to Table 6, but for Ashley Forest – H31883.

	Prediction equation	R-Squared
FFMC	+T850+U1000	0.33
DMC	+T850pc1-H1000pc3+T850pc3	0.19
DC	+T850pc1+T850pc3+H1000pc1	0.10
ISI	+U1000+T850pc1	0.33
BUI	+T850pc1-H1000pc3+T850pc3	0.19
FWI	+T850pc1-H1000pc3+U1000	0.34
DSR	-H1000pc3+T850pc1+U1000	0.25

At Ashley Forest (Table 15) both warmer temperatures (T850 or T850p1) and westerly wind fields regionally (U1000) were the best predictors for FFMC and FWI.

Multiple regression analysis at Balmoral Forest (Table 16) also showed the warmer temperatures and westerly wind fields regionally as important together with vorticity (Vort) for FFMC, ISI, FWI and DSR.

Table 16 Similar to Table 6, but for Balmoral Forest - H22783.

	Prediction equation	R-Squared
FFMC	+T850+U1000+Vort	0.25
DMC	+T850pc1+T850pc3+H1000pc1	0.14
DC	+T850pc1+T850pc3+H1000pc1	0.08
ISI	+U1000+T850+Vort	0.34
BUI	+T850pc1+T850pc3+H1000pc1	0.14
FWI	-H1000pc3+T850pc1+U1000+Vort	0.36
DSR	-H1000pc3+T850pc1+U1000+Vort	0.32

Table 17 Similar to Table 6, but for Bottle Lake - H32451.

	Prediction equation	R-Squared
FFMC	+T850+Vort+U1000+H1000pc1	0.19
DMC	+T850pc1+T850pc3-H1000pc1-H1000pc2	0.15
DC	+T850pc1+T850pc3	0.07
ISI	+U1000+T850pc1+Hp1	0.22
BUI	+T850pc1+T850pc3	0.13
FWI	-H1000pc3+T850pc1+T850pc3	0.19
DSR	+U1000+T850pc1	0.17

Relationships at Bottle Lake (Table 17) were weaker, with variance explanations low for various fire weather indices. This site produced less consistent results to other Canterbury sites examined.

At Darfield (Table 18), regional temperature and westerly wind occurrence were the predictors identified for FWI, with vorticity and anticyclonic conditions (H1000pc1) important for FFMC.

Table 18 Similar to Table 6, but for Darfield - H32416.

	Prediction equation	R-Squared
FFMC	+T850+U1000+H1000pc1+Vort	0.30
DMC	-H1000pc3+T850pc1+T850pc3	0.21
DC	+T850pc1+T850pc3	0.09
ISI	+U1000+T850pc1	0.31
BUI	-H1000pc3+T850pc1+T850pc3	0.20
FWI	+U1000+T850pc1	0.33
DSR	+U1000+T850pc1	0.26

Table 19 Similar to Table 6, but for Snowdon - H31594.

	Prediction equation	R-Squared
FFMC	+T850+U1000+Vort+T850pc3	0.33
DMC	+T850pc1+T850pc3-H1000pc3+H1000pc1	0.22
DC	+T850pc1+T850pc3	0.11
ISI	+U1000+T850pc1	0.27
BUI	+T850pc1+T850pc3-H1000pc3+H1000pc1	0.22
FWI	+U1000+T850pc1-H1000pc3+Vort	0.36
DSR	+T850pc1-H1000pc3	0.22

Finally at Snowdon (Table 19) FFMC and FWI had regional temperature and westerly wind patterns as predictors along with vorticity and H1000pc3.

The derived relationships have not been tested on real-time forecast model output, as the period of data for the forecast model is outside the period of data for the Fire Service station information, hence no validation of FWI forecasts was possible with the data sets available.

Summary: The best relationships were found between FFMC, FWI and Daily Severity Rating (DSR) with westerly wind strength, and for more eastern stations with higher atmospheric temperature. Nearest climate station maximum temperatures and earth temperatures were also well related to FFMC, FWI and DSR, notably in those stations farthest east. In Canterbury, stronger westerly winds and higher temperatures are associated with higher FFMC and FWI. The variance accounted for in regressions on FFMC and FWI typically ranged from 20 to 30%, for contemporary relationships (today’s FWI values from today’s weather).

6. Discussion

Generally, the Fine Fuel Moisture Code (FFMC) has the highest correlation with any of the NCEP and observed climate predictors in all the fuel moisture code indexes, while the Fire Weather Index (FWI) has the highest correlation in all the fire behaviour indexes. However, there are striking difference between Northland and Canterbury regions. For Northland, FFMC and FWI are mostly significantly correlated with regional averaged vorticity and the rainfall amount at the closest NIWA stations (rain), while for Canterbury, FFMC and FWI are mostly significantly correlated with maximum temperature (Tmax) and the regional averaged westerly wind component (U1000).

In the case of Northland, positive (anticyclonic) regional mean vorticity, regional averaged southerly wind strength (V1000), the positive second principal component of H1000 (H1000pc2 – southerly flow) and the negative third principal component of regional H1000 field (H1000pc3 – ridges over Northland) are associated with positive FFMC and FWI.

The leading five empirical orthogonal functions (EOF) of the regional H1000 and

T850 are shown in Figure 6 (reproduced from Figure 2 of Renwick et al. 2007). The positive polarity of H1000 PC2 indicates southerly conditions over New Zealand. Since Northland is well sheltered from the southerly there would be a strong drying effect over which also creates warmer and drier conditions. A negative H1000 PC3 represents a ridge over Northland which also creates warmer and drier conditions. On the other hand, more positive vorticity (i.e.anticyclonic conditions, with decreased storminess, upward motion and lower rainfall) also indicates less moisture and drier conditions.

The level of skill for Northland, based on the variance accounted for in regressions on FFMC and FWI ranging from 15 to 25%, suggests limited skill in forecast mode, on the order of 10-15% explained variance.

For Canterbury, more significant FFMC and FWI are associated with the regional averaged westerly flow (U1000), the negative H1000p3 (westerly flow), the positive regional T850 and the first principal component of T850 field (T850pc1) (higher temperatures).

The negative H1000pc3 and stronger U1000 all indicate stronger westerlies. Since Canterbury is well sheltered from the west, stronger westerlies would be associated with more significant foehn effect, creating warmer and drier conditions over the region. From Figure 6, PC1 of T850 indicates a higher temperature centre near Canterbury. Therefore, both positive T850 and T850pc1 indicate warmer conditions over the region, which are also associated with higher fire risk in the region.

The variance accounted for in regressions on FFMC and FWI from 20 to 30%, which is somewhat higher than that found for Northland, suggests some skill in forecast mode, on the order of 15-20% explained variance.

It seems that there is a significant difference in the behaviour of fire risk between Northland and Canterbury. For Canterbury, temperature seems a dominant factor for fire danger ratings/fire weather severity. This may be because temperature variability in Canterbury is much greater than in Northland, and rainfall and moisture content is relatively lower. In Northland, the temperature is generally higher and less variable than that in Canterbury, and conditions are more humid. Therefore, low moisture becomes a more important factor for when higher fire danger ratings/more severe fire weather/fire danger in Northland. This conclusion is also consistent with that derived by the correlation analysis.

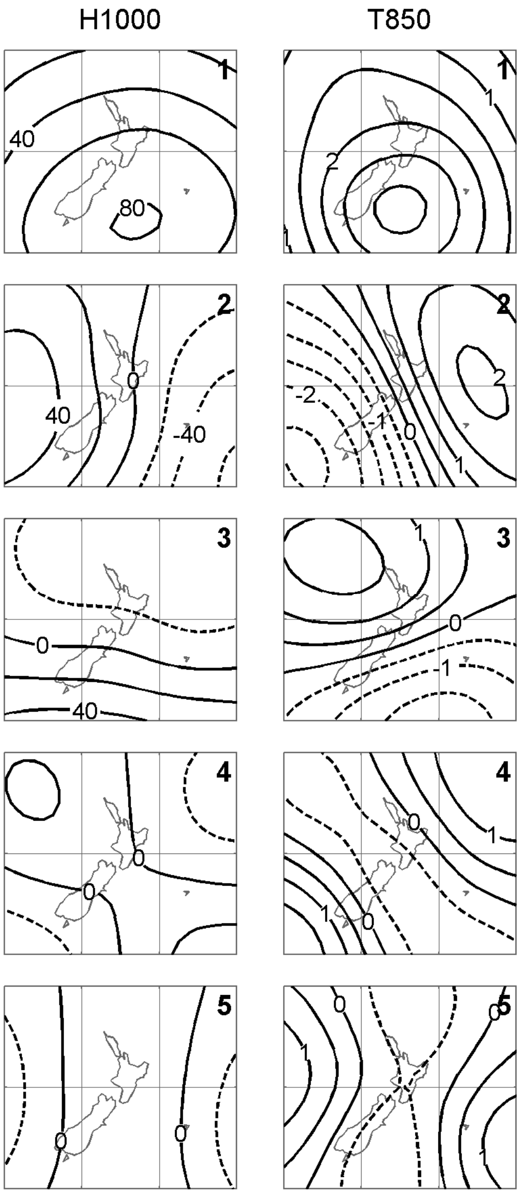

Figure 6: The leading 5 principal components of the 1000hPa height (H1000) field (left) and the 850hPa temperature (T850) field (right) over the New Zealand region, for the period 1989-2003. Fields are shown exhibiting typical amplitude for a time series (PC) value of +1 standard deviation. For H1000, units are geopotential metres and the contour interval is 20 m. For T850, units are °K and the contour interval is 0.5 °K. Negative contours are dashed throughout. From Figure 2, Renwick et al (2007).

Because of the level of skill found in contemporary diagnostic relationships between weather/climate variables and elements of the FWI System, it seems likely that individual daily predictions of FWI components would not exhibit useful skill in an operational sense. Similarly, extending the approach to monthly predictions, given the levels of skill found here, is also unlikely to produce operationally useful results. It is however possible that weekly (or other multi-day) averages of FWI components may be skilfully predicted from averaged weather information.

In future years, it would be worthwhile validating the relationships developed here, in forecast mode (after updating Fire Service observational data sets), and to assess the utility of estimating weekly (or other multi-day) averages of FWI components, rather than daily values. Multi-day smoothing may remove some of the less predictable variability in the FWI values, possibly revealing stronger relationships with averaged weather and climate variables. Further investigation of the Daily Severity Rating (DSR), in particular, warrants further investigation as it is the FWI System component most suited to averaging over specific periods to produce, for example, weekly (WSR) or 10-day (TSR) severity ratings (Harvey et al. 1986, Pearce and Moore 2004). Hence, while the research conducted here has not produced immediate results, the approach indicated does hold some promise and warrants further investigation.

7. Conclusions

The diagnostic downscaling relationships developed here exhibit explained variances on the order of 20% and up to 30% in some cases. The derived relationships have not been tested on real-time forecast model output, as the period of data for the forecast model is outside the period of data for the Fire Service station information, hence no validation of FWI forecasts was possible with the data sets available. However, given experience with NIWA predictions of daily climate variables, where diagnostic explained variances are around 40% or so, it seems likely that real-time prediction of daily FWI System components would be of marginal skill for operational use, as found by Simmers (2005).

Acknowledgements

Fire weather indices for Northland and Canterbury were supplied by the National Rural Fire Authority.

References

Alexander, M.E. 1992. Fire danger rating and fire behaviour prediction. Lecture to New Zealand Certificate in Forestry (NZCF) Stage V course 5170, Protection and Environmental Studies, September 17, 1992, Forestry Training Centre, Rotorua. 25 p.

Anderson, S.A.J. 2006. Future options for fire behaviour modelling and fire danger rating in New Zealand. Paper No. 75, presented at the Bushfire Conference 2006, Brisbane, 6-9 June 2006. 6 p. CD-ROM.

Andrews, P.L.; Bradshaw, L.S. 1990. RXWINDOW: defining windows of acceptable burning conditions based on desired fire behaviour. USDA Forest Service, Intermountain Research Station, Ogden, Utah. General Technical Report INT-GTR-273. 54 p.

Andrews, P.L.; Bradshaw, L.S.; Bunnell, D.L.; Curcio, G.M. 1998. Fire danger rating pocket card for firefighter safety. In: Proceedings of the Second Conference on Fire and Forest Meteorology, 11-16 January 1998, Phoenix, Arizona. pp 67-70.

Anon. 1993. Fire Weather Index System Tables for New Zealand. National Rural Fire Authority in association with the New Zealand Forest Research Institute. Wellington, N.Z. 48 p.

Auer, A. 1997. MetFax Seasonal Forecast covering November-December 1997. Issued 5 November 1997. Meteorological Service of New Zealand Ltd.

Borger, B.H. 1997. Closure of Conservation Lands for Public Safety Reasons: Fire Danger on Somes Island, Wellington, New Zealand. Department of Conservation, Wellington. Unpublished Report. 22 p.

Cooper, A.N.; Ashley-Jones, C. 1987. Economics of fire prevention in New Zealand plantations. *New Zealand Forestry 31(4)*: 14-18.

Fogarty, L.; Slijepcevic, A. 1998. The influence of wind speed on the effectiveness of aerial fire suppression. New Zealand Forest Research Institute, Forest and Rural Fire Research Programme. Fire Technology Transfer Note 17 (February 1998). 8 p.

Fogarty, L.G.; Pearce, H.G.; Catchpole, W.R.; Alexander, M.E. 1998. Adoption vs. adaptation: lessons from applying the Canadian Forest Fire Danger Rating System in New Zealand. In: Proceedings, 3rd International Conference on Forest Fire Research and 14th Fire and Forest Meteorology Conference, Luso, Coimbra, Portugal, 16-20 November, 1998. pp 1011-1028.

Fogarty, L.G.; Smart, P.N.; 1994. The development of initial attack guides and incident management structures. Paper presented to the Central North Island Forest Companies Fire Cooperative, July 1994, Waiotapu.

Gosai, A.; Griffiths, G.; Salinger, J. 2004. Climate and severe fire seasons: Part IV – Daily weather sequences and high fire severity in Auckland, West/Waikato, North Canterbury, McKenzie Basin and Central Otago/Inland Southland. Report prepared for the National Rural Fire Authority. National Institute of Water and Atmospheric Research Ltd, Auckland. NIWA Client Report (National Rural Fire Authority) AKL2003-026. 32 p.

Gosai, A.; Heydenrych, C.; Salinger, J. 2003. Climate and severe fire seasons: Part III – Climate patterns and high fire severity in Northland and Canterbury. Report prepared for the National Rural Fire Authority, March 2003. National Institute of Water and Atmospheric Research Ltd, Auckland. NIWA Client Report(National Rural Fire Authority) AKL2003-024. 19 p. + Appendices.

Gray, H.W.; Janz, B. 1985. Initial-attack initiatives in Alberta: a response to the 1980s. In: Proceedings of the Intermountain Fire Council 1983 Fire Management Workshop, October 25-27, 1983, Banff, Alberta. Canadian Forestry Service, Northern Forestry Research Centre, Edmonton, Alberta. Information Report NOR-X-271. pp 25-36.

Griffiths, G. 2004. Climate and severe fire seasons: Part V – Daily weather sequences and high fire severity in Auckland East/Coromandel, Bay of Plenty, Gisborne/Hawke’s Bay, Manawatu/Wairarapa, Wellington/Nelson/Marlborough and coastal Otago. National Institute of Water and Atmospheric Research Ltd, Auckland. Client Report (National Rural Fire Authority) AKL2004-135. 25 p. + Appendices.

Harrington, J.B.; Flannigan, M.D.; Van Wagner, C.E. 1983. A study of the relation of components of the Fire Weather Index to monthly provincial area burned by wildfire in Canada 1953-80. Canadian Forest Service, Chalk River, Ontario. Information Report PI-X-25.

Harvey, D.A.; Alexander, M.E.; Janz, B.. 1986. A comparison of fire-weather severity in northern Alberta during the 1980 and 1981 fire seasons. *Forestry Chronicle 62(6)*: 507-513.

Heydenrych, C.; Salinger, J. 2002. Climate and severe fire seasons: Part II – New Zealand fire regions. National Institute of Water and Atmospheric Research Ltd, Auckland. NIWA Client Report (National Rural Fire Authority) AK02045. 46 p.

Heydenrych, C.; Salinger, J.; Renwick, J. 2001a. Climate and severe fire seasons. National Institute of Water and Atmospheric Research Ltd, Auckland. NIWA Client Report (National Rural Fire Authority) AK00125. 117 p.

Heydenrych, C.; Salinger, M.J.; Renwick, J.A. 2001b. Climate and fire season risk: Factors contributing to severe fire seasons in New Zealand. In: Proceedings, Bushfire 2001 Conference, Joint Bushfire/FRFANZ Conference, Christchurch, 3-6 July 2001. pp 54-60.

Kalnay, E.; Kanamitsu, M.; Kistler, R.; Collins, W.; Deaven, D.; Gandin, L.; Iredell, M.; Saha, S.; White, G.; Woollen, J.; Zhu, Y.; Chelliah, M.; Ebisuzaki, W.; Higgins, W.; Janowiak, J.; Mo, K.C.; Ropelewski, C.; Wang, J.; Leetmaa, A.; Reynolds, R.; Jenne, R.; Joseph, D. 1996. The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society* 77**:** 437-471.

McAlpine, R.S. 1990. Seasonal trends in the Drought Code component of the Canadian Forest Fire Weather Index System. Forestry Canada, Petawawa National Forestry Institute, Chalk River, Ontario. Information Report PI-X-97E/F. 36 p.

NIWA. 1999. *The Climate Update*. National Institute of Water and Atmospheric

Research, National Climate Centre for Monitoring and Prediction. No. 1 (16 July 1999).

NIWA. 2004. Seasonal Fire Weather Climate Outlook, October – December 1999, and updates through 2004. The forecasts were posted on the NRFA website.http://nrfa.fire.org.nz/fire_weather/niwa.index.htm.

OMNR. 1989. Guidelines for modifying forest operations in response to fire danger. Ontario Ministry of Natural Resources, Aviation Fire Management Centre, Sault Ste. Marie, Ontario. 13 p.

Pearce, G. 1996. An initial assessment of fire danger in New Zealand's climatic regions. New Zealand Forest Research Institute, Forest and Rural Fire Research Programme. *Fire Technology Transfer Note 10* (October 1996). 28 p.

Pearce, H.G.; Douglas, K.L.; Moore, J.R. 2003. A fire danger climatology for New Zealand. Forest Research Contract Report No. 10052, prepared for the New Zealand Fire Service Commission Contestable Research Fund. 289 p. [New Zealand Fire Service Commission Research Report No. 39].

Pearce, H.G.; Majorhazi, K. 2003. Application of fire behaviour to fire danger and wildfire threat modelling in New Zealand. In: Conference Proceedings, 3rd International Wildland Conference, 3-6 October 2003, Sydney, Australia. 10 p. CD-ROM.

Pearce, H.G.; Moore, J.R. 2004. Use of long-term fire danger data sets to predict fire season severity. Forest Research Contract Report (Output 37940) (New Zealand Fire Service Commission Contestable Research Fund). 25 p. + Appendices.

Pearce, H.G.; Mullan, A.B.; Salinger, M.J.; Opperman, T.W.; Woods, D.; Moore, J.R. 2005. Impact of climate change on long-term fire danger. National Institute of Water and Atmospheric Research Ltd, Auckland. NIWA Client Report (New Zealand Fire Service Commission Contestable Research Fund) AKL2005-45. 70 p. [New Zealand Fire Service Commission Research Report No. 50].

Pearce, H.G.; Salinger, J.; Renwick, J. 2007. Impact of climate variability on fire danger. National Institute of Water and Atmospheric Research Ltd, Auckland. NIWA Client Report (New Zealand Fire Service Commission Contestable Research Fund) AKL2007-XX. (in press).

Renwick, J.A.Thompson, C.S.; Mullan, A.B.; Porteous, A. 2007. Short-term climate prediction from ensemble NWP. *International Journal of Climatology*, in draft form.

Salinger, M.J.; Heydenrych, C.;Renwick, J. 2002. Climate and severe fire seasons. In: Proceedings, Forest and Rural Fire Association of New Zealand Annual Conference, Auckland, 7-9 August 2002.

Simard, A.J. 1973. Forest fire weather zones of Canada. Environment Canada, Canadian Forestry Service. (Poster with text).

Simmers, T. 2005. Medium range forecasts of fire weather indices: an assessment of canonical correlation based forecasts from an ensemble prediction system. Report prepared by the Meteorological Service of New Zealand Limited for the NZ Fire Service Commission, 1 December 2005.

Valentine, J.M. 1978. Fire danger rating in New Zealand: review and evaluation. New Zealand Forest Service, Forest Research Institute, Production Forestry Division, Rotorua. Forest Establishment Report No. 123. 53 p.

Van Wagner, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Government of Canada, Canadian Forestry Service, Ottawa, Ontario. Forestry Technical Report 35. 37 p.

Van Wagner, C.E.; Pickett, T.L. 1985. Equations and FORTRAN program for the Canadian Forest Fire Weather Index System. Government of Canada, Canadian Forestry Service, Ottawa, Ontario. Forestry Technical Report 33. 18 p.

Williams, A.A.J. 1998. Observed extreme fire weather in Australia and the impact of ENSO. *Proceedings, 13th Conference on Fire and Forest Meteorology*, 27-31 October 1996, Lorne, Australia. International Association of Wildland Fire. pp. 279-285.

Wotton, B.M.; Flannigan, M.D. 1993. Length of fire season in a changing climate. Forestry Chronicle 69(2): 187-192.

Wotton, B.M., B.J. Stocks, M.D. Flannigan, R. Laprise and J-P. Blanchet. 1998. Estimating future 2xCO2 fire climates in the boreal forest of Canada using a regional climate model. *Proceedings, 3rd International Conference on Forest Fire Research and 14th Fire and Forest Meteorology Conference*, Luso, Coimbra, Portugal, 16-20 November, 1998. pp 1207-1221.