Fire weather of a Canterbury Northwester on 6 February 2011 in South Island, New Zealand

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Abstract

Foehn winds, known locally as the "Canterbury Northwester", occurred on 6 February 2011 and were associated with extreme fire weather in the lee of the Southern Alps and across the eastern South Island of New Zealand. A peak air temperature of 40.7˚C was recorded at Timaru, which compares with the national record of 42.4˚C set at Rangiora in 1973 during another Northwester. The primary objective of this study was to investigate the fire weather and the synoptic and mesoscale atmospheric processes associated with the Northwester. This was achieved through analysis of weather station data and a high-resolution Weather Research and Forecasting (WRF) model simulation. The fire weather was assessed through consideration of observable weather variables and New Zealand's version of the Fire Weather Index (FWI) in the Canadian Forest Fire Danger Rating System. The WRF model results suggest that internal gravity waves were present in the lee of the Southern Alps and considerably affected fire weather across the eastern South Island. The FWI was recorded at extreme values, due to a combination of high air temperatures and wind speeds, and low relative humidity. This study provides a better understanding of the mesoscale atmospheric dynamics and fire weather associated with the Canterbury Northwester.

Introduction

Foehn winds are a type of warm and dry wind that descend along the leeward slope of sizable mountain ranges. They are commonly referred to by a local name, such as the Chinook and Santa Ana winds in North America, and the Föhn wind in the Europe. Foehn winds are typically associated with a sudden increase in air temperature and decrease in relative humidity on the leeward side of the mountain range. In addition, they can be associated with orographic upwind blocking, and internal gravity waves and downslope windstorms in the lee of the mountain range. Foehn winds and their associated atmospheric processes can considerably affect fire weather near mountainous terrain (Whiteman 2000; Sharples 2009).

The South Island of New Zealand is situated in the mid-latitudes of the Southern Hemisphere and therefore experiences prevailing westerly synoptic winds. The Southern Alps mountain range extends approximately 450 km from the southwest to the northeast of the South Island and has a considerable effect on regional weather and climate (Sturman *et al.* 1999). Northwesterly foehn winds that occur on the eastern side of the Southern Alps, which predominantly affect the central South Island regions of Canterbury and Otago, are locally known as the "Canterbury Northwester", "Northwester" or "Nor'wester". The spatial and temporal characteristics of several Northwesters, and their effects on local wind systems in the Canterbury Plains and Southern Alps, have previously been studied using observational data (Lamb 1975; McGowan and Sturman 1996; McGowan *et al.* 2002).

It is understood that the Northwester can considerably affect fire weather and behaviour in the eastern South Island. For example, the 1973 Ashley Forest fire in Canterbury (Beatson 1985; Pearce and Alexander 1994) and the 1995 Berwick Forest fire in Otago (Fogarty *et al.* 1997), both exhibited high intensity fire behaviour and occurred during a Northwester. However, there has been limited research into the fire weather conditions and wildland fire behaviour associated with the Northwester (Steiner 1979).

This study aims to investigate the fire weather conditions, and the synoptic and mesoscale atmospheric processes, associated with a Northwester that occurred on 6 February 2011. Although there were no major recorded wildland fires on this day, the Northwester resulted in widespread extreme fire weather conditions across the eastern South Island. A peak air temperature of 40.7˚C was observed at Timaru, compared with the New Zealand record of 42.4˚C set at Rangiora on 7 February 1973, the same day of the Ashley Forest Fire. A combination of numerical weather prediction (NWP) modelling and weather station data are used to investigate the fire weather characteristics of this Northwester.

Numerical Weather Prediction Model

Version 3.4 of the Weather Research and Forecasting (WRF) NWP model (Skamarock *et al.* 2008) was used to simulate the synoptic and mesoscale atmospheric processes associated with the Northwester that occurred on 6 February 2011. The WRF NWP model was chosen as it is well suited to mesoscale atmospheric modelling and is widely used by the scientific research and operational weather forecasting communities. The WRF model simulation covered the five day period from 1200 NZST on 3 to 8 February 2011.

Three domains with two-way nesting were used, and the domains had a horizontal grid spacing of 18, 6 and 2 km, and a computational domain of 120x120, 193x193 and 391x391 grid points, respectively. The outer model domain covered all of mainland New Zealand and extended far out into the Pacific Ocean and Tasman Sea, whereas the two nested domains principally covered just the South Island. The three domains shared an identical configuration of 50 vertical levels, which extended from 16 m AGL to a fixed model pressure top at 10 hPa. The whole outer model domain was nudged at six-hourly intervals, with a default nudging time scale of approximately one hour, using the National Centers for Environmental Prediction (NCEP) Final Analyses (FNL).

The WRF model utilises fully compressible non-hydrostatic equations and has a mass-based terrain-following coordinate system. The microphysics were represented by a single-moment six-class scheme with mixed-phase processes. The sub-grid scale effects of convective or shallow clouds were modelled only in the outer domain using a modified Kain-Fritsch scheme. The surface layer and planetary boundary layer were represented by the Eta schemes. The heat and moisture fluxes over land were provided by the Noah Land Surface Model, which has soil temperature and moisture in four layers, fractional snow cover and frozen soil physics. A simple short-wave radiation scheme and the Rapid Radiative Transfer Model represented the radiation physics. A gravity wave damping layer was used to prevent reflection of gravity wave energy off the upper boundary.

Fire Weather Assessment

New Zealand's version of the Fire Weather Index (FWI) System, used in the Canadian Forest Fire Danger Rating System (Van Wagner 1987), is the primary operational tool used to assess fire weather in New Zealand and is a principal component of the New Zealand Fire Danger Rating System (NZFDRS) (Alexander 1992; Anderson 2005). The FWI itself is a fire behaviour index that quantifies the expected fire intensity for a reference fuel type and is derived from the near-surface air temperature, relative humidity, wind speed and rainfall. An FWI ≥ 32 generally corresponds to an "Extreme" fire danger classification for forested regions in New Zealand (Alexander 2008). The fire weather conditions are assessed using a combination of WRF model output and observational data taken from weather stations located across the South Island, as shown in Figure 1.

Synoptic Meteorology

At 1200 NZST on 6 February 2011, a high pressure system was located northwest of the North Island, and a cold front was approaching the South Island from the southwest, as shown in Figure 2. A ridge of high pressure was present over the Southern Alps, with a lee trough on the downwind side. Figure 3 demonstrates that the pressure gradient from the northwest to the southeast of the South Island was ~14 hPa, or ~2 hPa per 100 km, which is fairly typical relative to other Northwesters (McGowan and Sturman 1996). The subsequent passage of the cold front over the South Island on 7 February eliminated this pressure gradient across the South Island and brought predominantly southerly and southwesterly synoptic flow across the southern and central South Island. A visual comparison of the observed and modelled pressure differences across the South Island indicate that there are only minor differences prior to the arrival of the cold front.

The modelled wind conditions at 10 m AGL at 1200 NZST on 6 February, shown in Figure 4a, indicate limited orographic blocking of the low-level northwesterly synoptic winds by the central Southern Alps. This is in agreement with the northerly to northeasterly 10 m AGL wind direction measured at Hokitika throughout 6 February. The model results further suggest that, prior to and during the onset of the foehn winds, low-level synoptic winds were channelled through the Cook Strait, and curved inwards back towards the South Island's eastern coast due to the lee trough. This is consistent with the northeasterly 10 m AGL wind direction measured at Christchurch late on 5 February and early on 6 February, prior to the onset of the northwesterly foehn winds from 1000 NZST on 6 February. These are fairly typical characteristics of the Canterbury Northwester (McGowan and Sturman 1996, McCauley and Sturman 1999).

Gravity Waves

The modelled vertical wind velocities, at 2 km above mean sea level (AMSL), and MODIS satellite imagery from 6 February are shown in Figures 4b and 5. The vertical wind velocities at 2 km AMSL suggest that internal gravity waves were present in the lee of the Southern Alps during the Northwester. In the southern South Island, the modelled gravity waves propagated far downstream, indicating the presence of trapped lee waves. Regularly spaced gravity wave cloud formations can be seen over the southern South Island in the MODIS images, which broadly supports the model results.

Vertical cross-sections of the modelled potential temperature and wind speed at 1200 NZST on 6 February, shown in Figure 6, indicate that the atmosphere was stable upwind of the Southern Alps. These stable atmospheric conditions helps explain the presence of the low-level northeasterly barrier flow along the central western coast of the South Island. Hydraulic jump features, in which the high velocity downslope lee flow rises sharply as it encounters a low velocity flow region, were present in the WRF model results in the lee of the central Southern Alps and along the foothills of the Canterbury Plains. These hydraulic jump features were associated with modelled wind speeds exceeding 120 km h^{-1} along the foothills of the Canterbury Plains. Downwind of the internal hydraulic jumps, the modelled wind speeds were comparatively low at 0-30 km h^{-1}.

In the southern South Island, trapped lee waves were modelled downwind of the Southern Alps, which extended out across the eastern South Island and Pacific Ocean. The modelled lee waves extended from near the surface to a height of ~10-12 km, with modelled wind speeds exceeding 120 km h^{-1} above ~2 km AMSL. The modelled near-surface wind speeds were high under the lee wave troughs and on mountain lee slopes, and comparatively low under the lee wave crests and on mountain windward slopes. In contrast to the central South Island, there were no hydraulic jump features modelled in southern half of the South Island.

Fire Weather

The magnitude of the modelled warming and drying effect of the Northwester in the lee of the Southern Alps is clearly evident in Figures 7a and 7b. The Timaru station recorded the highest air temperature on 6 February 2011 at 40.7˚C, which compares with a daily maximum air temperature of 19.0˚C measured at the Hokitika station near the west coast. The WRF model did not fully capture this foehn warming effect, as demonstrated by Figure 8a, with a peak modelled air temperature at 2 m AGL of 34.8˚C in the central eastern South

Island. The observed relative humidity reached a daily minimum of 25.0 and 29.6 % at the Timaru and Christchurch stations, respectively. Both the observed and modelled relative humidity rarely dropped below 30%, as partly shown by Figure 7b, and were therefore fairly unremarkable in a fire weather context.

The modelled wind speed at 10 m AGL and the FWI were highest along the foothills of the Canterbury Plains, as shown in Figures 7c and 9a, due to the hydraulic jumps discussed above. The modelled daily maximum FWI, which is determined at hourly intervals, peaked at 75 in this region and is consistent with the daily maximum of 75 recorded at the Christchurch station. The modelled FWI was greater than 32, corresponding to an Extreme fire weather classification for forested regions, across much of the eastern South Island during the Northwester. A map of the daily FWI issued for New Zealand by the National Rural Fire Authority on 6 February 2011 is shown in Figure 9b for comparison.

The Snowdon station, which is located in the foothills of the Canterbury Plains, recorded a relatively low daily maximum wind speed and gust of 46.4 and 82.4 km h^{-1}, compared to the WRF model results (see Figure 8b). A similar daily maximum wind speed and gust of 51.3 and 85.2 km h^{-1} were measured further downwind at the Christchurch station. These combined results cast some doubt over the validity of the modelled internal hydraulic jumps in the central South Island. In the southern South Island, the WRF model results showed alternating bands of high and low near-surface wind speeds on the leeward and windward slopes, respectively, of the mountains. However, the modelled FWI was not as high in the southern South Island relative to the central South Island, due predominantly to the higher relative humidity further south.

Heavy orographic rainfall was modelled along the west coast of the southern half of the South Island, as shown in Figure 7d, with 3 hr rainfall quantities exceeding 50 mm in isolated regions at 1200 NZST on 6 February. This is in good agreement with the measured 3 hr rainfall of 55.8 mm at the Milford Sound station. Further north, there was only limited modelled rainfall along the west coast, with a 24 hr rainfall of 17.5 mm measured at the Hokitika station on 6 February. The passage of the cold front over the South Island on 7 February resulted in light to moderate rainfall across the southern and central South Island, which effectively reduced the FWI to zero.

Discussion and Conclusions

The Northwester that occurred on 6 February 2011 resulted in an Extreme fire danger classification being issued by the National Rural Fire Authority for much of the eastern South Island of New Zealand. The fire weather conditions and the synoptic and mesoscale atmospheric processes associated with the Northwester were investigated using a combination of weather station data and the WRF mesoscale NWP model. The synoptic meteorology and regional characteristics of the Northwester were broadly similar to that observed in other Northwesters (McGowan and Sturman 1996; McCauley and Sturman 1999).

The onset of the Northwester resulted in a sudden and considerable increase in air temperature, and decrease in relative humidity, across much of the eastern South Island. Timaru recorded the highest daily maximum air temperature of 40.7˚C, and air temperatures were in the high 30s across much of the central eastern and northeastern South Island. In contrast, the relative humidity was rarely below 30 % and so was fairly unremarkable in a fire weather context. However, the combination of high air temperatures and wind speeds resulted in extreme fire weather across the eastern South Island, as quantified by the FWI.

The considerable spatial and temporal variability of the FWI indicates that accurate prediction of the fire weather conditions associated with the Northwester is important for fire management decisions made during Northwester events. Although there were no major wildland fires on 6 February 2011, Northwesters are known to have contributed to high intensity fire behaviour during wildfires, such as in the 1973 Ashley Forest and 1995 Berwick Forest fires. Future work will focus on developing a climatology of Northwester events in the South Island and relate this to wildland fire occurrence and behaviour.

The WRF model results and MODIS satellite imagery suggest that trapped lee waves were present in the lee of the Southern Alps across the southern half of the South Island. These trapped lee waves were associated with alternating bands of low and high wind speeds along the upward and downward mountain slopes, respectively. The WRF model results suggest that hydraulic jump features were present in the central South Island along the foothills of the Canterbury Plains. However, the presence of these hydraulic jumps is not supported by the observational data at the Snowdown and Christchurch weather stations. The WRF model also under-predicted the peak air temperatures observed across the central eastern South Island on the order of several degrees celsius. Future work will expand the verification of the WRF model output through comparison with in-situ and remote measurements of the fire weather conditions made across the South Island. It is likely that the existing WRF model errors are due to a combination of factors, including the resolution of the high-relief terrain, model parameterisations and errors in the NCEP FNL used to nudge the outer model domain (Simpson *et al*. 2013).

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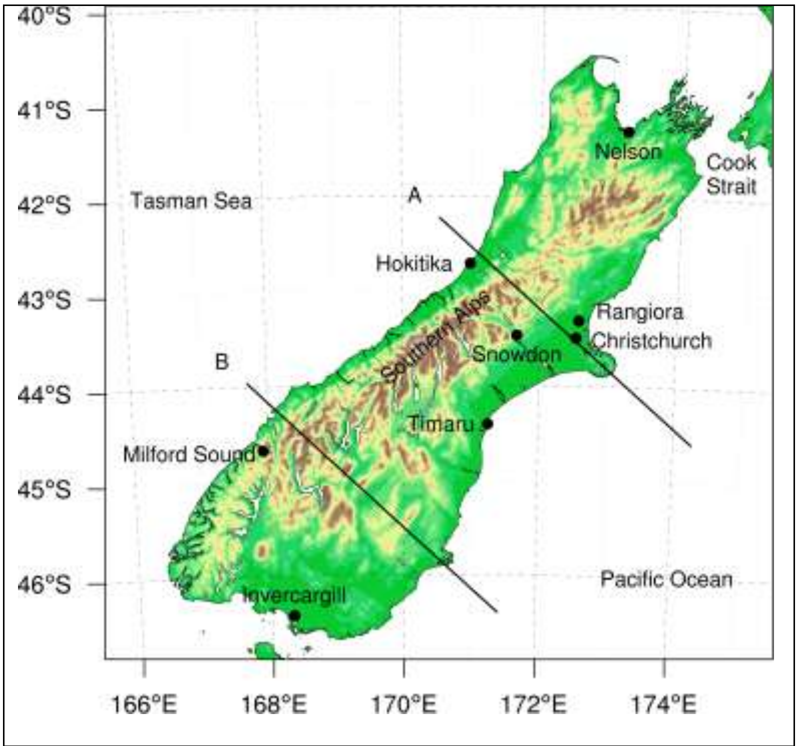

Figure 1: Map of the South Island of New Zealand showing the location of weather stations, geographical features and vertical cross-sections shown in Figure 5.

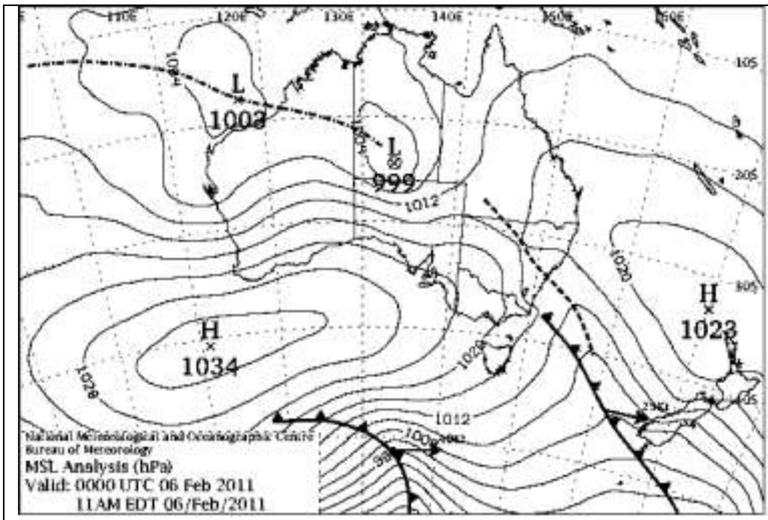

Figure 2: MSLP chart for the Australia and New Zealand region at 1200 NZST 6 February 2011, with a contour interval of 4 hPa. Originally issued by the Bureau of Meteorology, Melbourne, Australia.

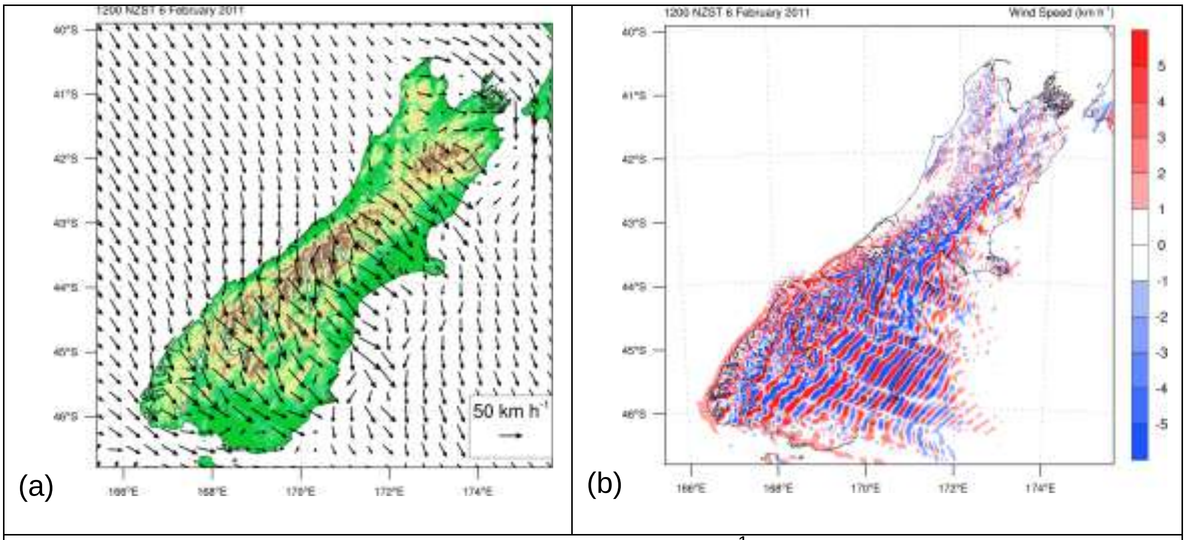

Figure 3: Modelled (a) horizontal wind conditions (km h^{-1}) at 10 m AGL and (b) vertical wind velocity (km h^{-1}) at 2 km AMSL at 1200 NZST on 6 February 2011 for the inner model domain. In (a) the reference vector in the bottom right-hand corner shows a westerly wind of 50 km h^{-1}.

Figure 4: MODIS satellite composite images of New Zealand taken at (a) 1415, 1550 and 1555 NZST on 6 February 2011.

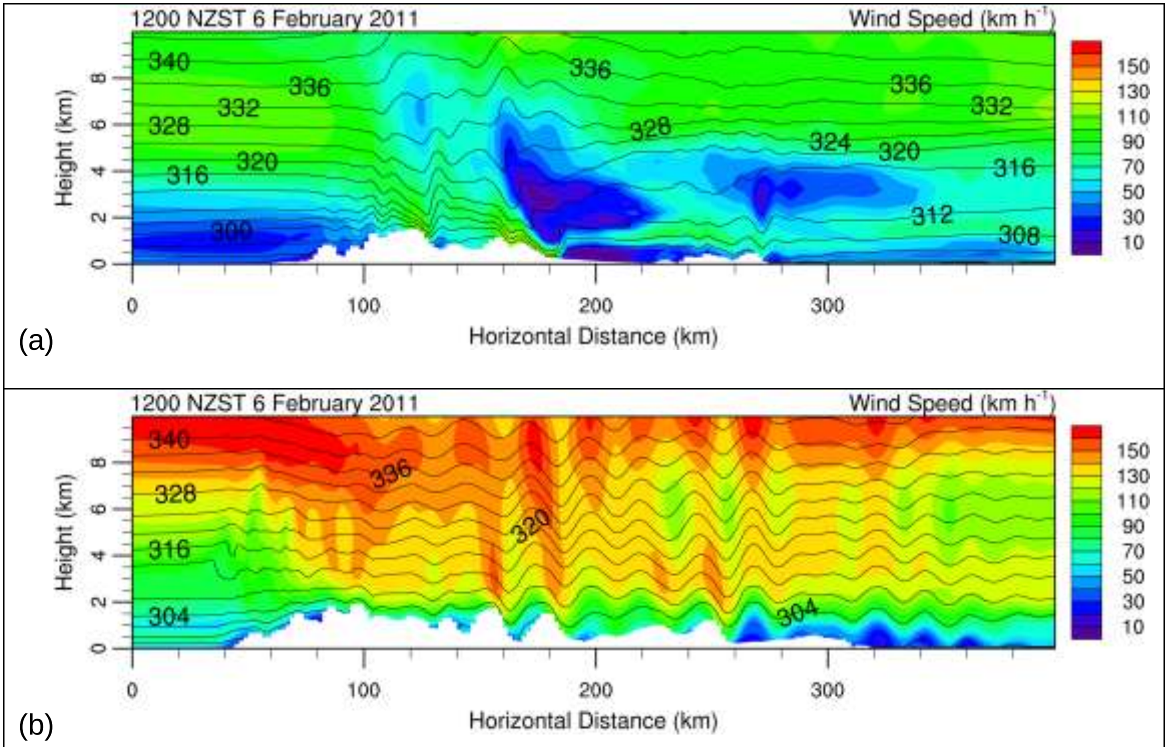

Figure 5: Vertical cross-section of the modelled potential temperature (K), which has a contour line interval of 4 K, and wind speed (km h^{-1}), which is colour shaded. The two cross-sections correspond to lines (a) A and (b) B in Figure 1a.

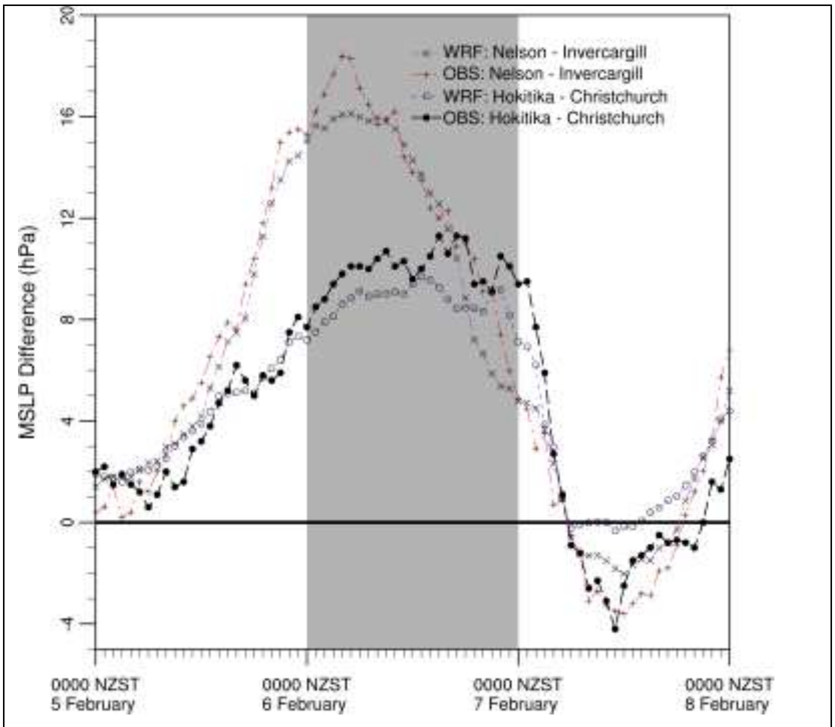

Figure 6: Time series of observed (OBS) and modelled (WRF) MSLP (hPa) difference between Nelson and Invercargill, and Hokitika and Christchurch. The horizontal black line indicates a pressure difference of 0 hPa.

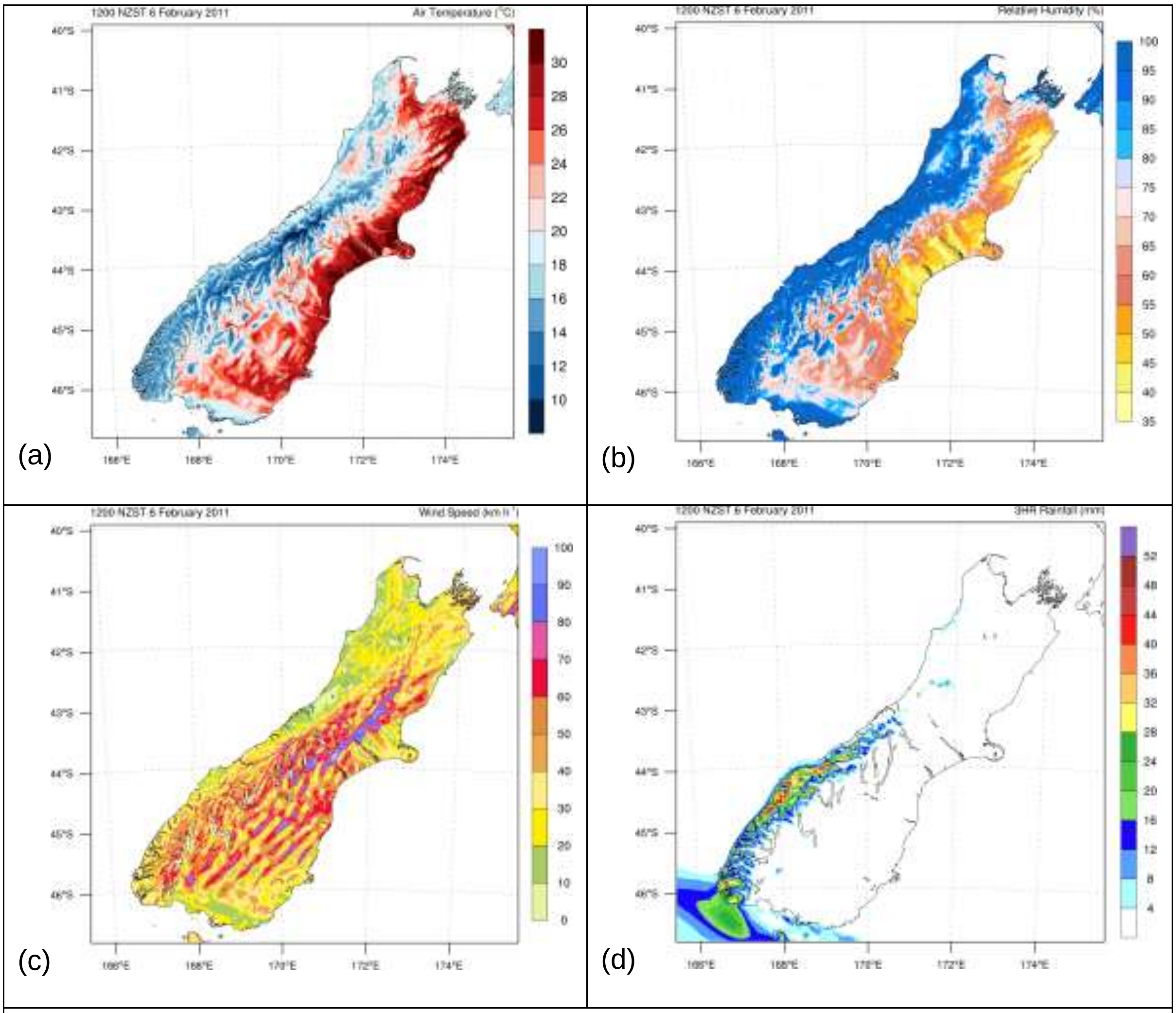

Figure 7: Modelled 2 m AGL (a) air temperature (˚C) and (b) relative humidity (%), (c) 10 m AGL wind speed (km h^{-1}), and (d) 3-hr rainfall (mm) at 1200 NZST on 6 February 2011 for the inner model domain.

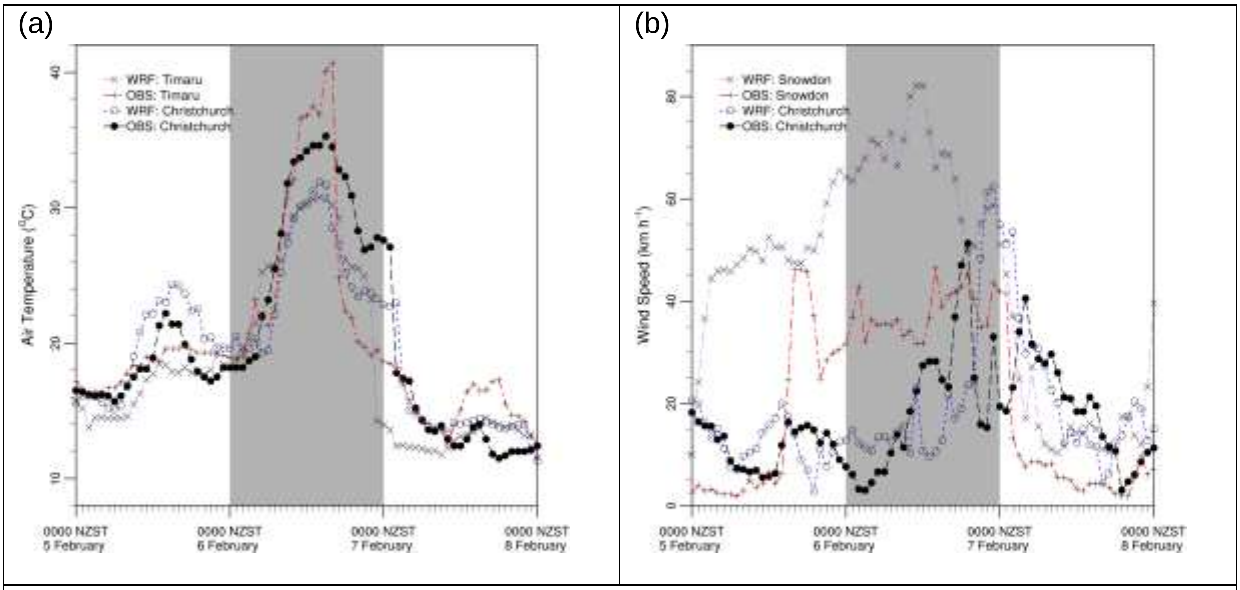

Figure 8: Time series of the observed (OBS) and modelled (WRF) (a) 2 m AGL air temperature (˚C) at Timaru and Christchurch, and (b) 10 m AGL wind speed (km h^{-1}) at Snowdon and Christchurch.

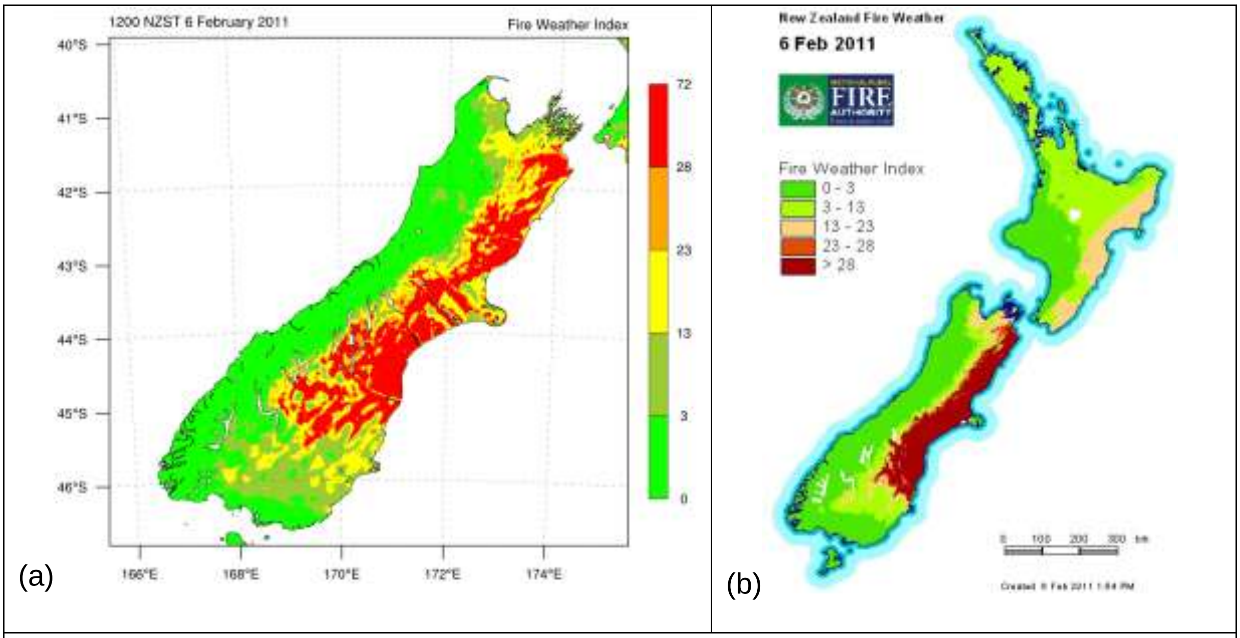

Figure 9: Daily FWI on 6 February 2011 (a) derived from WRF model results for the inner model domain and (b) issued by the National Rural Fire Authority for mainland New Zealand.