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Wind vector change and fire weather index in New Zealand as a modified metric in evaluating fire danger

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ABSTRACT

Background. Wildfire spread is influenced significantly by the weather variability. Wind speed and direction changes, resulting from synoptic weather systems and small-scale meteorological processes in complex terrain, can drastically alter fire intensity and spread. **Aims.** To investigate the use of vector wind change (VWC) integrated with the Fire Weather Index (FWI) as a new metric in fire danger. **Methods.** A 20-year FWI and modified FWI was calculated from weather station and gridded numerical weather simulation data. **Key results.** High VWC is found primarily on the South Island, inland and in areas of complex terrain. After incorporating VWC into the FWI, data from the modified FWI show spatiotemporal patterns that highlight the impact of wind variability in the fire danger. **Conclusions.** High VWC station data mapped with synoptic type suggest the primary factor in determining high VWC is meso- and micro-scale terrain-driven meteorology, not larger synoptic regimes. **Implications.** The current fire danger metric, the Fire Weather Index (FWI), does not include wind direction changes for high wind speeds. Therefore, the inclusion of VWC as an additional metric in fire danger calculations in a modified FWI could increase operational understanding of high-danger locations and terrain impacts on extreme and unpredictable fire behaviour.

Keywords: danger, fire behaviour, fire severity, FWI, mesoscale meterology, vector wind change, weather, wildfire risk.

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Introduction

Wildfire behaviour is highly dependent on near-surface meteorological conditions (Werth *et al.* 2016). Wildfire danger increases with low atmospheric humidity, strong winds, drought and unstable air conditions (Harris *et al.* 2017; Mills *et al.* 2020). These elements are inter-dependent and have a significant impact on extreme and unpredictable fire behaviour. In complex terrain, wildfire behaviour can be influenced by dynamically and thermally driven wind systems (Werth *et al.* 2016). A dynamically driven wind is channelled and amplified by the topography, whereas thermally driven wind systems are driven by pressure gradients associated with local and regional air temperature gradients. New Zealand's complex terrain, including mountain ranges, valley systems and complex coastal topography, means that near-surface wind systems are a critical variable to understand to better predict wildfire danger (Hilton *et al.* 2015; Dong *et al.* 2021).

Wildfire in New Zealand

Until the last 5 years, large-scale wildfires were an infrequent occurrence in New Zealand. However, like in many countries around the world, wildfires are increasing in size and frequency with warmer and drier weather (Simpson *et al.* 2014; Pearce 2018). These fires are also increasingly encroaching on urban spaces (Pearce 2018). This trend is illustrated in the recent 2017 Port Hills, 2019 Pigeon Valley and 2020 Ōhau fires in New Zealand. All three fires prompted evacuations of residents for multiple days and destroyed residential structures (AFAC 2017, 2019; Foley 2020).

To monitor fire danger around New Zealand, Fire and Emergency New Zealand (FENZ) and the National Institute of Water and Atmospheric Research (NIWA) collect hourly weather data from over 250 stations. From this weather station network, the Fire Weather Index (FWI) is routinely calculated for operational use. The FWI combines individual indicators of fire behaviour potential, including the Initial Spread Index and Buildup Index, to give a more comprehensive evaluation of fire danger (Van Wagner 1987; Anderson 2005; Simpson *et al.* 2014).

Vector wind change

Wind change is an important variable in fire behaviour and can drastically alter fire prediction and intensity (Mills *et al.* 2020). Wind change in both speed and direction can occur at time scales of minutes to hours. Many firefighter entrapments are caused by sudden wind changes, happening within a few minutes, that can rapidly change the direction of fire spread. A shift in wind direction can cause the flank of a fire to become the head of the fire, creating significant danger for firefighters engaged in direct or indirect attack (Cheney *et al.* 2001). Two recent wildfires illustrate the significance of understanding wind changes for fire behaviour in New Zealand: the 2017 Port Hills and 2019 Pigeon Valley fires experienced sudden wind direction changes due to local sea breezes and strong nocturnal downslope flows that exacerbated unpredictable fire behaviour (AFAC 2017, 2019; Pretorius *et al.* 2020). In the 2017 Port Hills fire, complex terrain-driven winds under stable nocturnal atmospheric boundary layer conditions forced rapid spread of the fire downhill in two separate events, significantly altering the fire spread (AFAC 2017; Pretorius *et al.* 2020). Similarly, in the 2019 Pigeon Valley fire, several wind changes at high wind speeds increased the rate of fire spread, as well as unpredictable fire behaviour and spotting (AFAC 2019).

New Zealand's location in the mid-latitudes of the southern hemisphere means that it is impacted by synoptic circulation systems traveling eastwards over the country following the southern westerly wind belt (Kidson 2000). The lack of land mass in the Southern Ocean and around New Zealand results in rapidly moving southerly and southwesterly cold fronts behind prefrontal westerly winds (Sturman and Tapper 2006). The combination of complex topography and synoptic wind shifts results in sub-daily changes in near-surface air temperature, wind, humidity and precipitation that impact fire behaviour.

The current weather-based fire danger prediction tool, the FWI System, does not account for changes in wind direction. It consists of three fuel moisture codes and three fire behaviour indices that provide relative numerical ratings for various aspects of ignition potential and fire behaviour based solely on selected weather inputs for a reference fuel type (mature jack and lodgepole pine forest) on level terrain (Van Wagner 1987). The fuel moisture codes – the Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC) and Drought Code (DC) – reflect the net effects of air temperature, relative humidity, wind speed and rainfall on daily moisture gains and losses in three layers of litter and organic ground fuel of different depths. The three fuel moisture codes and wind speed are then linked in pairs to form two intermediate and one final index of fire behaviour – the Initial Spread Index (ISI), indicating relative fire spread potential, the Buildup Index (BUI), indicating the total amount of fuel available for combustion, and the final FWI value indicating the potential fire intensity (Van Wagner 1987; Wotton 2009). Although the ISI component indicates the effect of wind speed on fire spread, it is based on a 10-min average wind speed, so does not account for changes in wind direction. This is because the FWI System is designed to provide general indicators of fire danger potential across broad areas to support communication of prevailing fire-weather risk for the public and regional fire prevention and readiness planning. The second major subsystem of the Canadian and New Zealand fire danger rating systems, the Fire Behaviour Prediction (FBP) System (Forestry Canada Fire Danger Group 1992; Wotton *et al.* 2009), accounts for the effects of different vegetative fuel types and topography (slope and aspect) on site-specific fire behaviour. However, even it still only uses the standard FWI System inputs and outputs to predict fuel consumption, fire spread rates and intensity, as well as fire area and perimeter growth, such as the 10-m open wind speed and ISI. Therefore, utilising wind change as an additional prediction metric could help to include critical meteorological and climatological information for predicting and understanding wildfire danger in complex terrain.

The interconnected nature of wind speed, direction and complex terrain has been highly explored in the literature. In general, significant wind direction changes occur primarily at low wind speeds (Mahrt 2011). However, in complex terrain, sudden wind direction changes can also occur at much higher wind speeds. Vector Wind Change (VWC), or the difference in magnitude of the hourly wind vectors, has been proposed by Mills *et al.* (2020) as a metric for identifying wind changes to predict wildfire climatology and danger. VWC was also previously proposed as a wind metric underpinning the Wind Change Range Index (WCRI), which incorporates wind speed and direction to predict synoptic-driven wind changes (Huang and Mills 2006*a*, 2006*b*). VWC was used in both a temporal and spatial analysis over Victoria, Australia, and in a comparison with the WCRI, and was found to indicate the types of wind change critical for predicting wildfire severity (Mills *et al.* 2020).

This study presents an investigation of the spatial wind changes across New Zealand from hourly fire weather station and gridded numerical weather model data using the VWC parameter. This allows identification of locations that experience a high frequency of wind changes and could provide insight into the role of terrain in wildfire danger assessment. The proposed modification for the VWC-based

FWI is assessed based on climatological gridded numerical model weather data and demonstrated for two recent wildfire incidents in New Zealand. Given the danger of wind changes during a wildfire and the complex terrain of New Zealand, VWC is a potentially useful metric in both evaluating high fire danger from wind and evaluating danger of extreme and unpredictable fire behaviour during a fire. Although the FWI is a valuable metric, it does not include information regarding wind changes, and could be enhanced as a predictive metric by utilising VWC in locations with complex terrain where local variability in wind vector changes can mask the synoptic weather change signal.

Data and methods

Fire weather station and numerical weather prediction data

Observations from the FENZ fire weather stations were accessed from the New Zealand Modelling Consortium Open Environmental Digital Library (www.envlib.org) using the Tethys Python package (Kitteridge 2021). Stations with a complete time series between 1 January and 31 December 2020 (128 stations) were included. Meteorological data were logged at sub-hourly intervals, usually every 10 min, but only the last 10 min of the hour are included in the database.

Numerical weather simulation data (provided by MetService, New Zealand) from the Weather Research and Forecasting (WRF) model were used as hourly gridded meteorological data (accessed using Tethys from the New Zealand Modelling Consortium Open Environmental Digital Library and originally run by MetService (Kitteridge 2021). The WRF outputs hereafter are referred to as 'gridded data'. Available at 4-km grid resolution, the most recent complete year of data (2020) was used for the analysis in accordance with the fire weather station data. In order to validate the meteorological model, correlation coefficient (CC) and root square mean error (RMSE) were calculated between WRF model output and FENZ station data for the variables FWI, ISI, BUI, wind speed, relative humidity, precipitation and temperature.

Vector wind change and fire weather index

VWC, or the difference in hourly wind vectors, was calculated hourly for both gridded and station data, and then averaged over the year-long period. The vector wind change was calculated based on the difference of the west-to-east (U) and south-to-north (V) wind vector components at two consecutive hours (t) as shown in Eqn 1 below.

$$\mathrm{VWC}_t = \left|((U_t - U_{t-1})^2 + (V_t - V_{t-1})^2)^{1/2}\right| \qquad (1)$$

Only the magnitude of the VWC is used in this study. To determine the highest-danger stations, the top 20% quantile of VWC were labelled as high danger. High-danger stations were also analysed with the 12 Kidson synoptic regime classifications, which are further split into three main groups based on overall mean sea-level pressure systems: trough, zonal and blocking, and are labelled with letters describing the pressure system and location (Kidson 2000). VWC is further investigated within each synoptic regime for the year of data (Renwick 2021).

The FWI, based on temperature, relative humidity, wind speed and precipitation (Van Wagner 1987; Anderson 2005; Mandal *et al.* 2021) was calculated daily using the gridded and station data. The median FWI values were calculated for each location over the year-long period. For extreme FWI values, a threshold of 20 was chosen to represent the transition to very high and extreme fire intensities and fire danger potential above this value (Alexander 2010; Scion 2020). Unfortunately, as fire weather data are not directly archived against individual fire events in New Zealand, there are insufficient fire occurrence data to validate this against present wildfire activity. However, a number of major historical forest fires have occurred when FWI values exceed this value (Pearce and Alexander 1994), and overseas, large fires in Canada have been found to be more likely at FWIs above 20 (Amiro *et al.* 2004).

Modified Fire Weather Index ($\mathrm{FWI}_{\mathrm{mod}}$)

Wind varies from the weekly synoptic scale to the hourly mesoscale owing to different meteorological processes like frontal systems, land/sea breezes and valley thermal wind systems. In the original FWI, only noon-time wind speed is used. To include the wind variation impact into the FWI, this work added the daily VWC (24-h average from noon-time previous day to the current day) to the noon-time wind speed (WS) in the FWI calculation (Eqn 2).

$$\mathrm{WS}_{\mathrm{mod}} = \mathrm{WS}_{\mathrm{noon}} + \left|\overline{\mathrm{VWC}}\right|_{24\,\mathrm{h}} \qquad (2)$$

The modified wind speed ($\mathrm{WS}_{\mathrm{mod}}$) is then used as the wind speed input for the $\mathrm{FWI}_{\mathrm{mod}}$.

Results and discussion

Nationwide vector wind change from station data

A nationwide analysis of VWC using the fire weather station network shows distinct regional and topographic trends (Fig. 1). High mean VWC stations are located primarily on the South Island, with two exceptions on the lower North Island. Furthermore, the majority of high VWC stations are located in areas of inland complex terrain. This suggests that in New Zealand, there is a correlation between terrain complexity and VWC, and therefore terrain is a key factor in evaluating sudden wind changes. The low mean VWC values are increasingly located on the North Island, and on the South Island in coastal areas. This suggests coastal stations and stations on flat

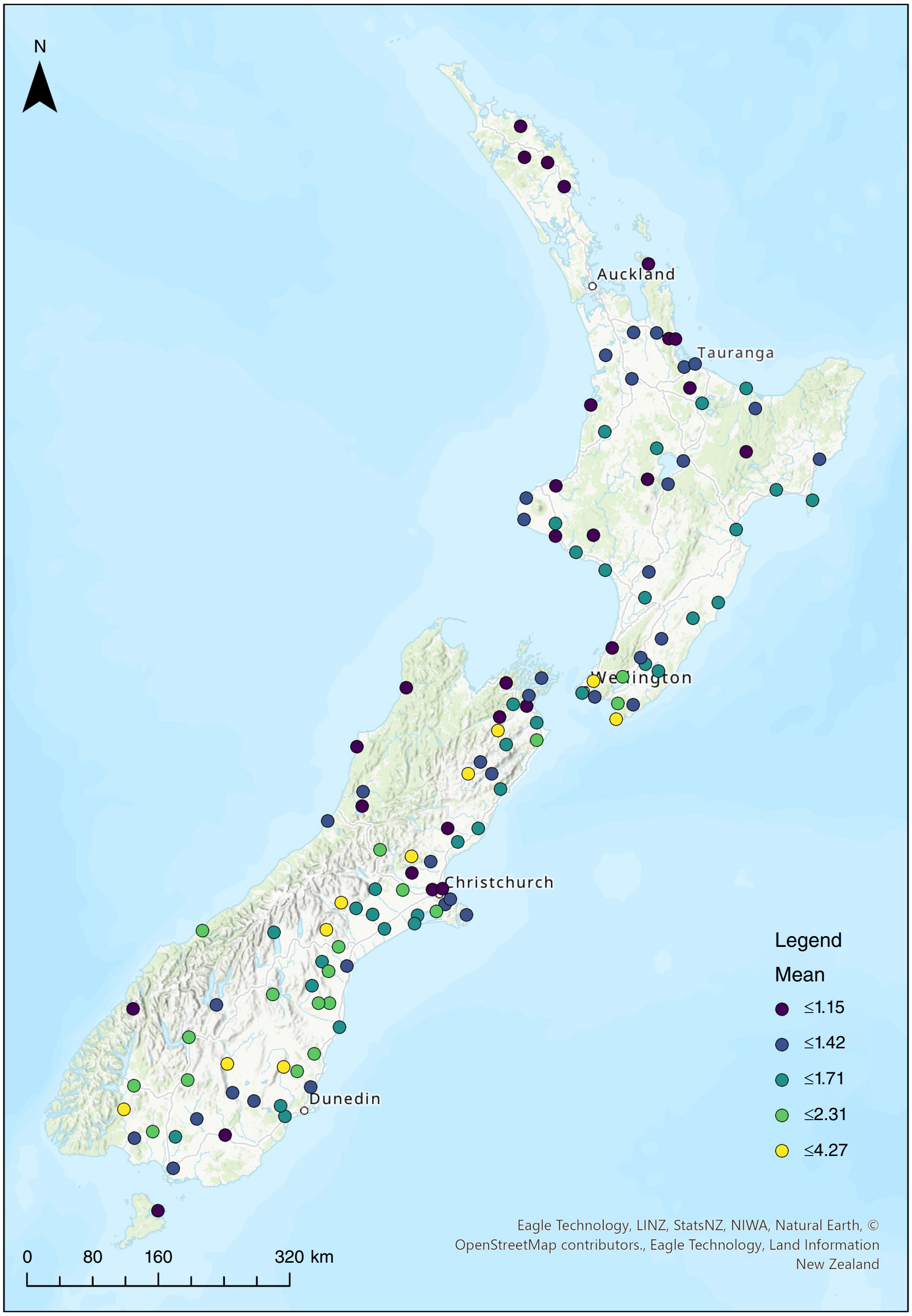

Fig. 1. Hourly Vector Wind Change (VWC) (m/s) annual mean for the year 2020 for all weather stations available from the Fire and Emergency New Zealand dataset.

terrain exhibit more consistent wind and wind direction leading to lower VWC values. This is likely due to slower wind direction and speed changes of the sea breeze cycle as compared with the sudden wind speed and direction changes from dynamically driven wind systems in mountainous areas.

Synoptic type impact on wind change

In order to better understand the variables affecting VWC across New Zealand, Kidson type, a synoptic weather type classification data, was applied to investigate spatial pattern changes of high VWC stations in regard to weather systems. There is some variation between synoptic regimes in the stations identified; however, the overall trend is consistent. High VWC stations appear primarily and consistently on the South Island in every synoptic regime (Fig. 2). There are multiple stations that appear in almost all synoptic types, located in Fiordland, mountainous Canterbury and the north of the South Island. This uniformity in stations with VWC across

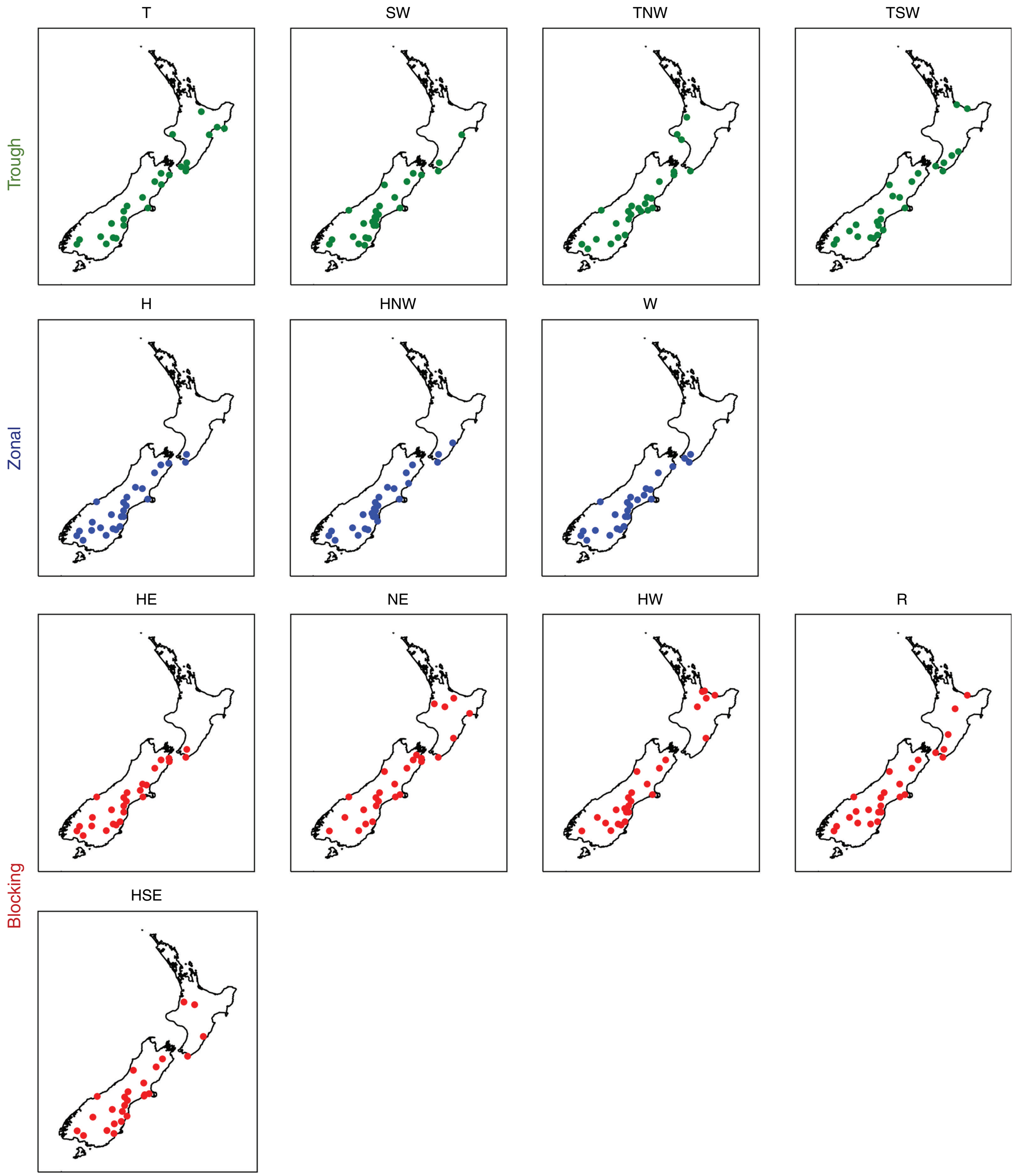

Fig. 2. The top 20% quantile, classified as 'high fire danger', Vector Wind Change (VWC) stations within each synoptic regime. First row is the trough group: from left to right are Trough (T), Southwesterly (SW), Trough-Northwesterly (TNW) and Trough-Southwesterly (TSW). Second row from left to right are High (H), High to the Northwest (HNW), Westerly (W) and High to the Southeast (HSE). H, HNW and W are the zonal group whereas HSE belongs to the blocking group. The last row is also the blocking group: from left to right are High to the East (HE), Northeasterly (NE), High to the West (HW) and Ridge (R). Synoptic regimes are based on the work of Kidson (2000) and Renwick (2021).

synoptic types suggests that the primary factor in these variables is terrain, not synoptic weather. Therefore, it is likely that some locations in New Zealand are at a higher danger of extreme fire behaviour regardless of synoptic type, owing primarily to location and proximity to complex terrain.

FENZ station vector wind change and fire weather index

The FWI was calculated for the FENZ weather stations at a daily time scale and averaged over the same year-long period as the VWC. The stations within the top 20% quantile

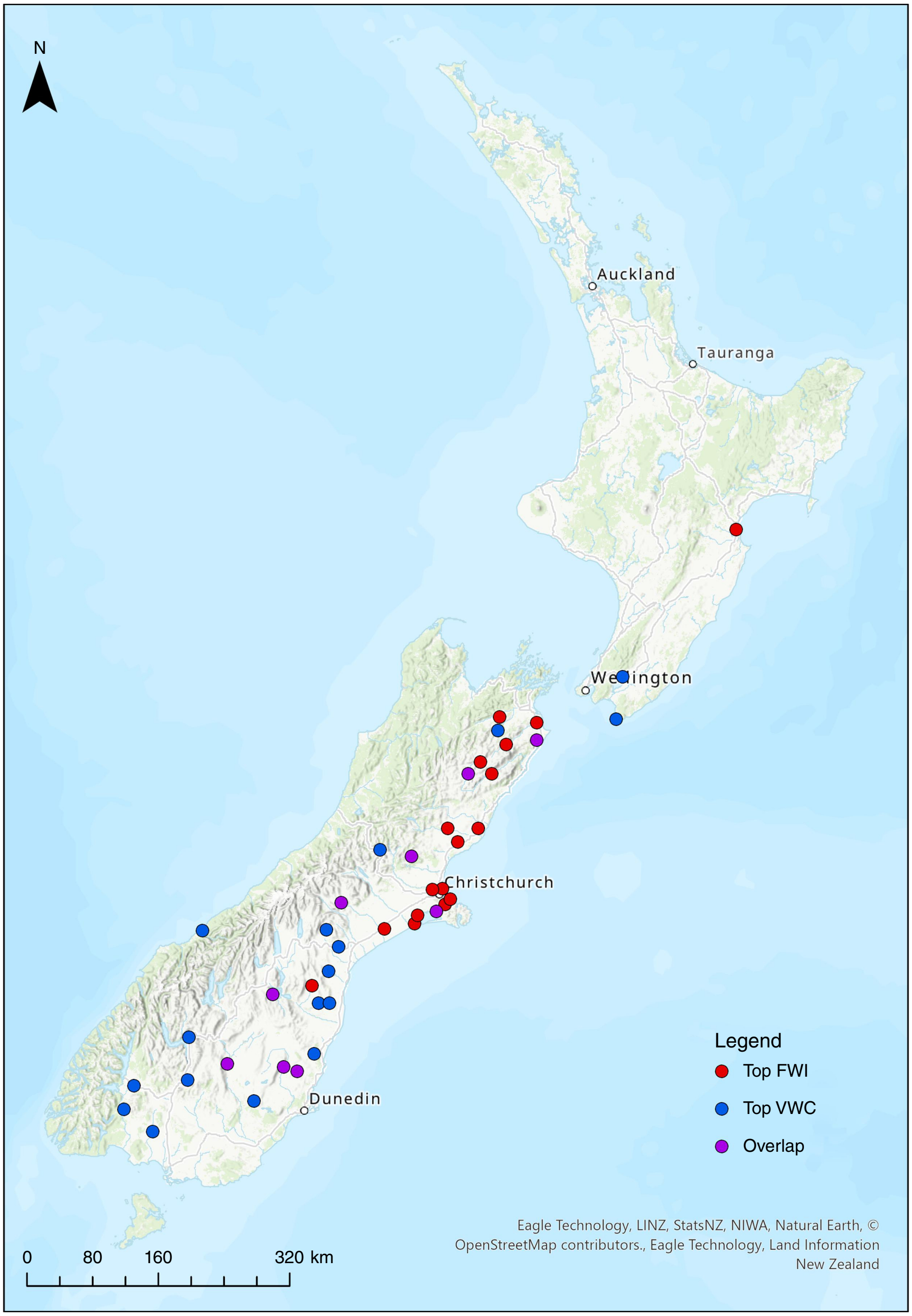

Fig. 3. Top 20% quantile Vector Wind Change (VWC) and top 20% quantile Fire Weather Index of all weather stations used in this analysis, and the stations in both top 20% for the two parameters.

of FWI were then mapped (Fig. 3) to compare with the top 20% quantile of the VWC stations. Interestingly, the same spatial trends appear in the high FWI stations as the high-danger VWC stations, with most of the stations on the South Island. In contrast to the VWC stations, however, high FWI stations are found in both coastal and inland locations. High FWI stations that do not overlap with VWC stations are found primarily in coastal areas or areas of less complex terrain, suggesting that the high FWI value is less dependent on wind speed. Of the high VWC stations, eight also appeared in the high FWI stations. This overlap in stations suggests that VWC could be a useful additional parameter for FWI calculations

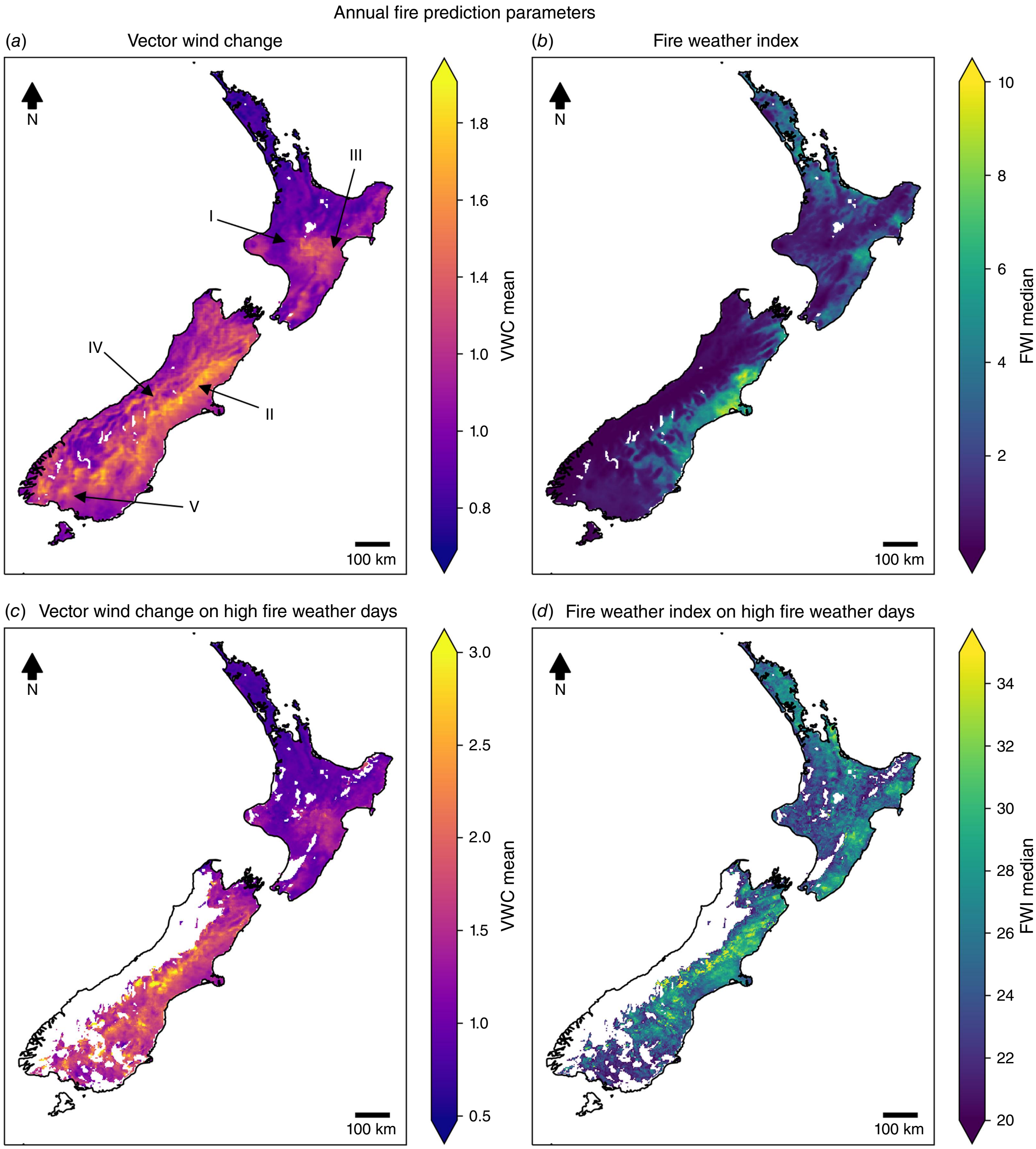

Fig. 4. (*a*) Mean daily Vector Wind Change (VWC), and (*b*) median daily Fire Weather Index (FWI) with 4 km gridded Weather Research and Forecasting model data from MetService for the year 2020, and (*c*, *d*) filtered for high-danger fire weather days in 2020 where FWI > 20. Regional references are inserted (*a*) for I (Ruapehu), II (Canterbury foothills), III (Gisborne), IV (West Coast), V (Southland).

around New Zealand to provide fire managers with additional information relating to the potential impact of wind changes in complex terrain on fire severity prediction.

Validation of WRF model gridded data for fire danger metrics

The correlation coefficients between the FENZ stations and the data obtained from the gridded weather model are within the range found in comparative literature, which have ranges 0.2–0.53 and 0.78–0.94 for wind speed and air temperature respectively as compared with 0.63 and 0.93 calculated for the present analysis (Pan *et al*. 2012; Banks and Baldasano 2016; Boadh *et al*. 2016; Avolio *et al*. 2017). Similarly, the RMSE is also comparable with other studies using WRF modelling in complex terrain, at 2.21 and 2.13 for wind speed and temperature, respectively (Avolio *et al*. 2017; Mughal *et al*. 2017; Solbakken *et al*. 2021). Based on the meteorological inputs, the FWI calculated for the station data and the WRF data has a correlation coefficient of 0.78, and an RMSE of 5.63. Therefore, the WRF model can be used as a good indicator of predictive fire parameters in locations without stations.

Spatial trends in gridded fire danger metrics

Fig. 4 shows the spatial distribution of the VWC and FWI represented by the annual mean (VWC) and median (FWI) (Fig. 4*a*, *b*), FWI greater than 20 (Fig. 4*d*), and the corresponding VWC for FWIs greater than 20 (Fig. 4*c*). The mean VWC is highest in the mountainous regions of the South Island, especially at the foothills of the Southern Alps towards the east. The correlation between high VWC and complex terrain is also shown in the North Island around Mounts Taranaki and Ruapehu and the Tararua range (Fig. 4*a*, I). The annual median FWI for the South Island also shows a relationship with terrain, with higher values concentrated in the Canterbury region on the eastern side of the Southern Alps (Fig. 4*a*, II). In the North Island, clusters of high FWI appear on eastern sides of the Taruarua and Te Urewera ranges, in the Hawkes Bay region and north of Gisborne (Fig. 4*a*, III). The VWC (Fig. 4*a*) and the FWI (Fig. 4*b*) are not always correlated across the same regions, which can be attributed to the more complex relationship between other meteorological parameters such as relative humidity, temperature and precipitation that underpin the FWI calculation, while the VWC only depends on changes in wind velocity. Examples for this negative correlation can be seen in Northland and Southland, and some parts of the West Coast (Fig. 4*a*, *b*). Annual medians of FWI with values greater than 20 (Fig. 4*d*) are largely concentrated on the South Island's eastern coast, and across the majority of the North Island. This spatial variability might be explained by the wetter conditions experienced on the South Island's West Coast (Fig. 4*a*, IV), drier and warmer conditions on the east coast of the South Island, and climatologically warmer conditions in the North Island (Fig. 5) (Macara 2021). The VWC locations corresponding to the high values of the FWI (Fig. 4*c*) exhibit similar spatial extents and variability to the high FWI (Fig. 4*d*) except for Northland (far north region of the North Island). Comparing Fig. 4*a*, *c*, in Southland (far south region of the South Island), most of the

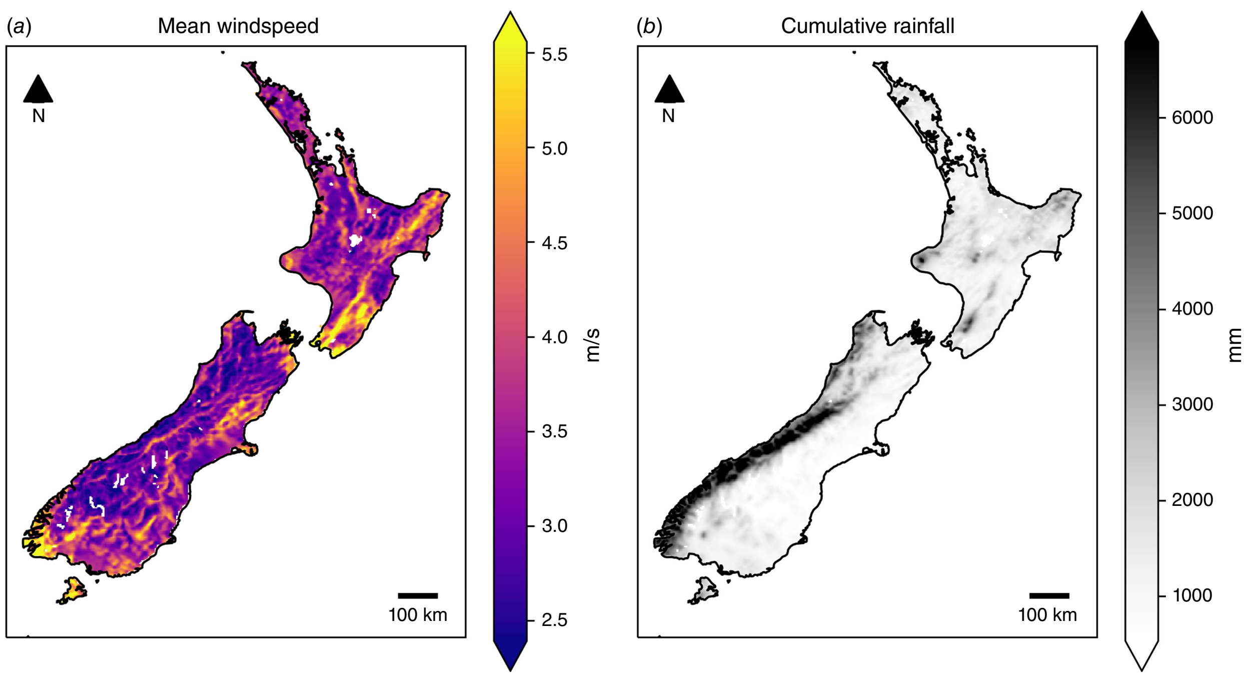

Fig. 5. (*a*) Mean annual windspeed; and (*b*) cumulative rainfall in 2020 from 4 km Weather Research and Forecasting model data.

high VWC values correspond to lower values in FWI, which may be related to the anomalous higher wind speed values in that region that are not necessarily the main drivers of the lower FWI (Fig. 4*a*, V).

Modified Fire Weather Index with vector wind change

Owing to the way that the 24-h VWC is added in the FWI_{mod} (as explained in Eqns 1, 2), it is expected that FWI_{mod} should

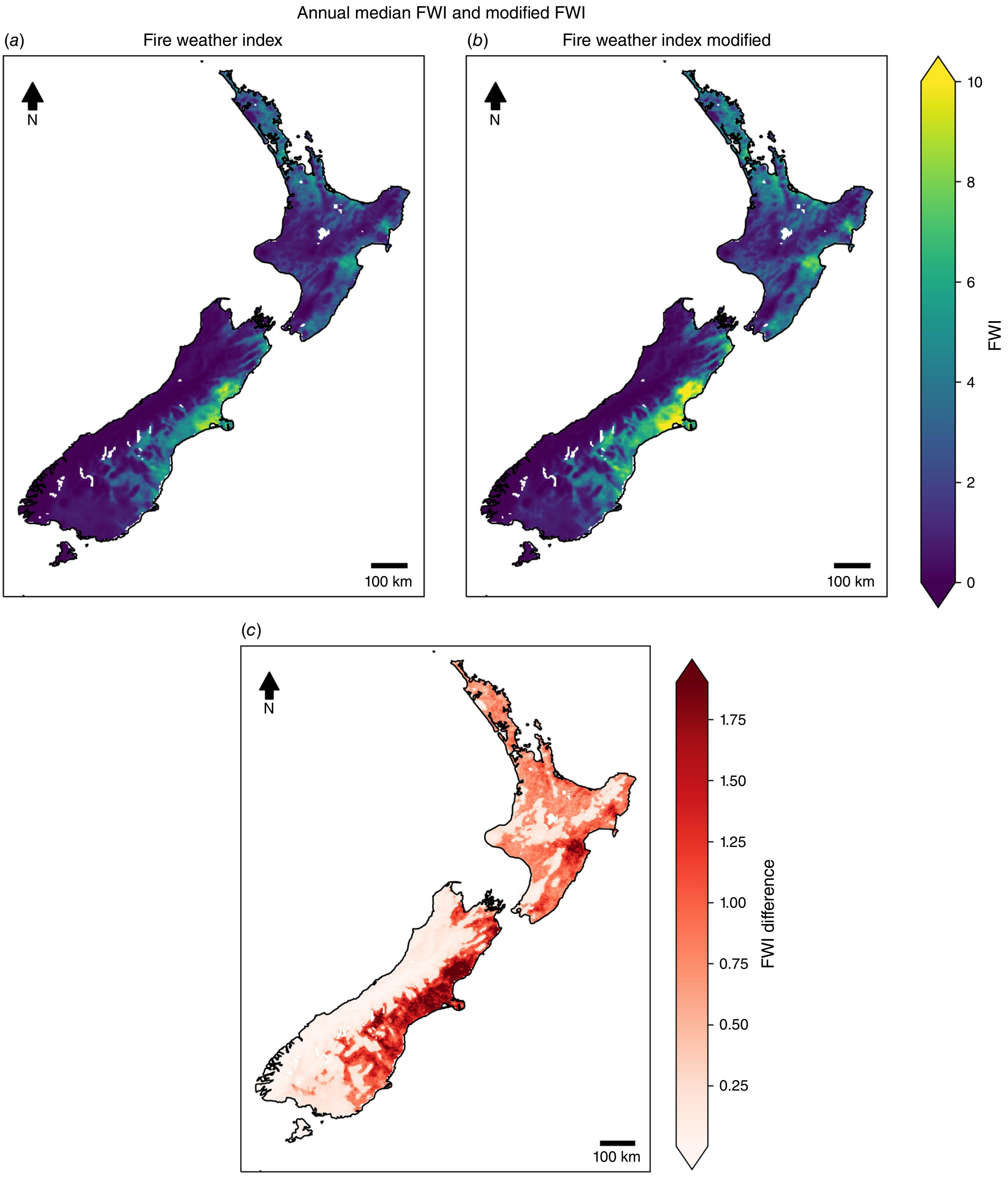

Fig. 6. (*a*) Median daily Fire Weather Index (FWI), and (*b*) modified median FWI (FWI_{mod}) that includes mean daily Vector Wind Change (VWC), and (*c*) the difference between FWI and FWI_{mod}, from 4 km gridded Weather Research and Forecasting model data from MetService.

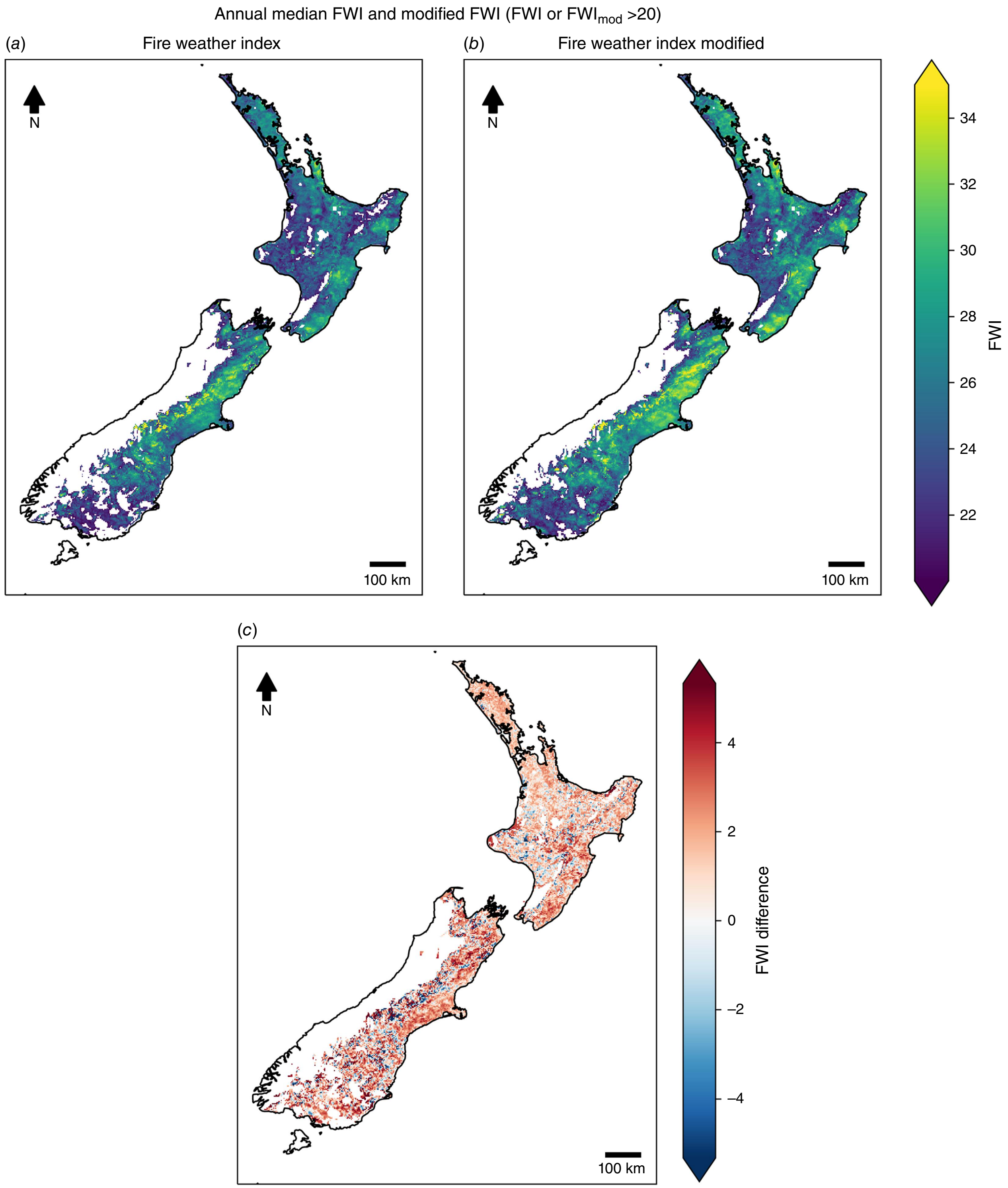

Fig. 7. (*a*) Median daily Fire Weather Index (FWI), and (*b*) modified median FWI (FWI_{mod}) that includes mean daily Vector Wind Change (VWC) and (*c*) difference between FWI and FWI_{mod} for high danger fire weather days only, where FWI or FWI_{mod} > 20. Data sourced from 4 km gridded Weather Research and Forecasting model data from MetService.

have higher values than FWI in general. This can be confirmed from the annual FWI map from 2020 (Fig. 6*a*, *b*). However, the increase is not spatially uniform. In fact, the difference between FWI_{mod} and the original FWI shows a distinctive spatial pattern, with the West Coast area of the South Island having almost no increase while some parts of the East Coast have more than 15% increase (Fig. 6*c*). Although the annual mean wind speed looks similar between the east and west coast of the South Island (Fig. 5*a*), the spatial variability of the VWC (Fig. 4*a*) matches the differences between the FWI_{mod} and FWI (Fig. 6*c*) well, with much higher VWC along the east coast. This shows that the modified FWI (FWI_{mod}) is successful in incorporating the impact of the wind variation and fluctuation (VWC). The median index from the high fire danger days, with index values higher than 20, also increases in most of the areas (Fig. 7).

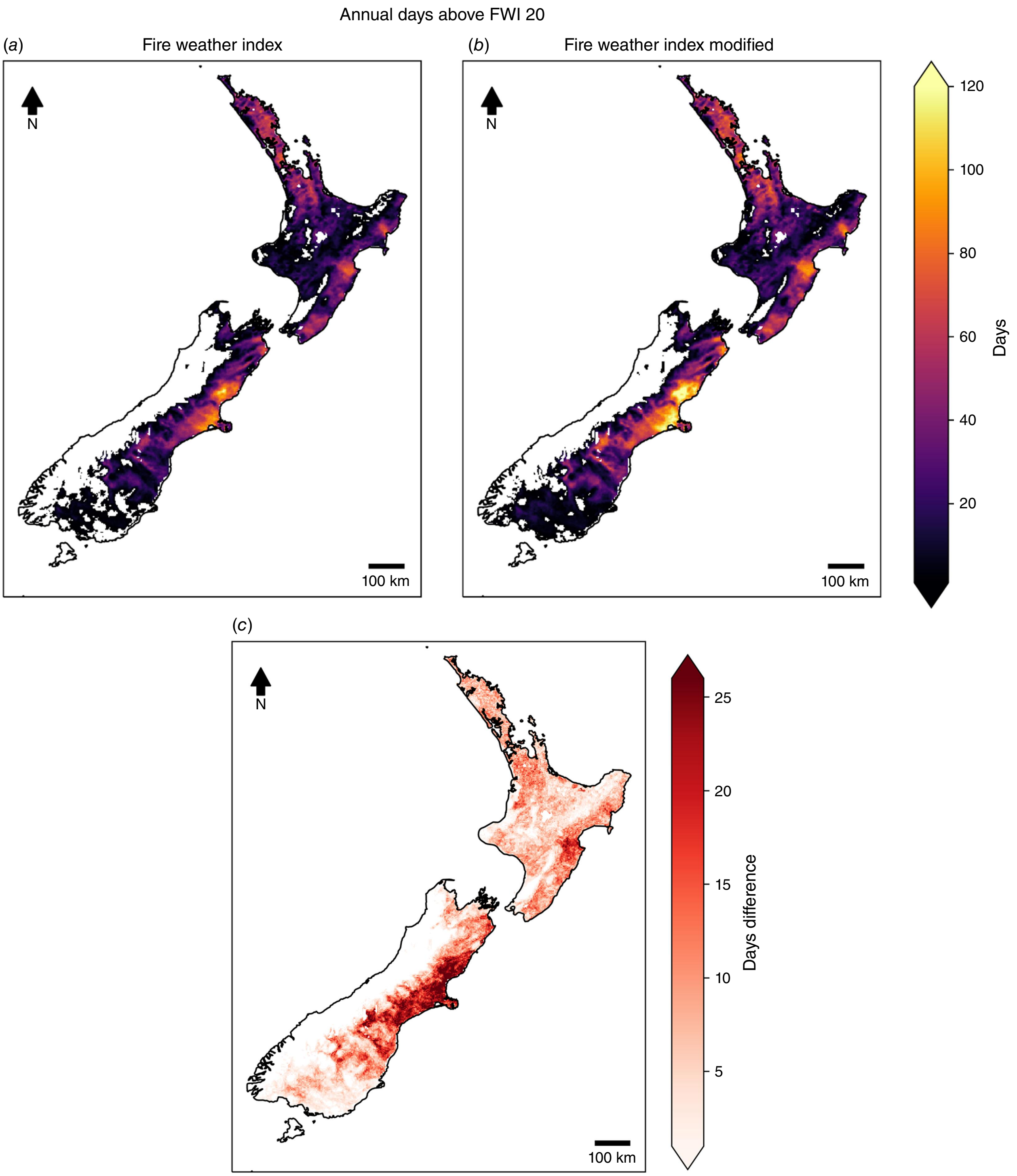

Fig. 8. Annual days in 2020 above (*a*) Fire Weather Index (FWI) 20, (*b*) modified FWI (FWI_{mod}) 20; and (*c*) difference in days above 20 between FWI and FWI_{mod}.

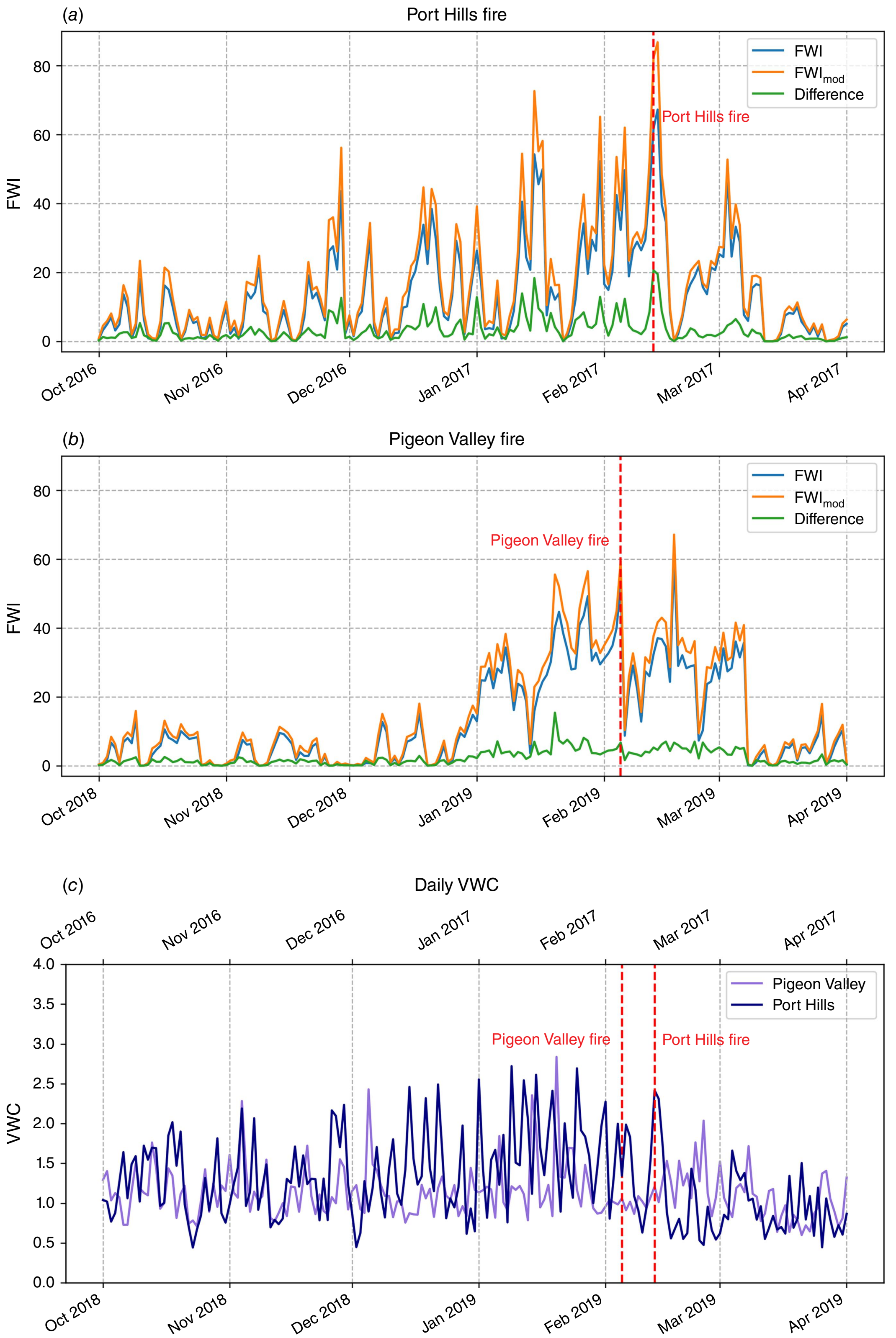

Fig. 9. (*a*) The 2017 Port Hills Fire Initial Spread Index (ISI) and Fire Weather Index (FWI), original and modified; (*b*) the 2019 Pigeon Valley fire FWI and modified FWI (FWI_{mod}); and (*c*) daily mean Vector Wind Change (VWC) for Port Hills and Pigeon Valley Fires. Meteorological data from 4 km Weather Research and Forecasting model dataset.

Although more verifications are needed, the higher index in the FWI_{mod} could indicate that when including the variability of the hourly wind change, the FWI_{mod} can be used to give the upper bound or the worst-case scenario prediction. WIth the high fire weather above FWI 20 (Fig. 7), some sites have a slight decrease of the FWI_{mod} index value. This is because some of the days that were previously below the high fire danger threshold in the original FWI have had their index increased to just above the threshold in the FWI_{mod}. When averaging the data in these locations, these new days just above the FWI threshold cause the median FWI_{mod} to be slightly lower than for the standard FWI. In the FWI_{mod}, a larger proportion of New Zealand, especially of the South Island, experiences days above FWI 20. This trend can also be seen in the annual cumulative days of high FWI (Fig. 8). When the FWI_{mod} is used, the Canterbury region experiences the largest increase in days above FWI 20 (Fig. 8*c*), with some areas increasing by more than 25 days per year with high fire weather danger. Overall, FWI_{mod} is shown to place a greater emphasis and weighting on the role of wind changes in fire danger potential around New Zealand by utilising the addition of VWC as a variation metric in the FWI calculation.

Case study analysis of Port Hills and Pigeon Valley fires

In the Port Hills fire, the most extreme fire behaviour occurred on the day of ignition (13 February) and 2 days later (on 15 February) when the two fires merged following a significant wind change to the NE (Pretorius *et al.* 2020). Fig. 9*a* shows the FWI and FWI_{mod} values peaking on the day the fire broke out, and increasing over the following 2 days, with the influence of the added VWC effect and its persistence over this period clear in the maximum peak in the difference (indicated by the green line, index values by up to 20) between the original and modified FWI values. This trend is not seen as significantly for the Pigeon Valley fire (Fig. 9*b*), even though the ignition time of the fire does occur during a slight increase in FWI_{mod}. The differences of the increasing magnitude of the FWI_{mod} compared with FWI between the Port Hill and Pigeon Valley cases highlight the nature of the added VWC component. When comparing the VWC during the Port Hill fire with the Pigeon Valley fire (Fig. 9), it is clear that the VWC is much higher during the Port Hill fire period. This again supports the use of FWI_{mod} in incorporating the VWC factors into the fire danger assessment. The value of FWI_{mod} increases significantly when there is a significant vector wind change but remains close to the original FWI otherwise.

Conclusions

A long term (20-year) spatial climatology of VWC and FWI was developed for New Zealand using gridded hourly outputs from a national database of numerical weather model simulations. An evaluation year was selected to compare the WRF-derived VWC and FWI with station-based observations. VWC is a useful near-surface variable for understanding potential wildfire occurrence conditions and their severity around New Zealand. This metric is primarily forced by the impact of complex terrain on wind speed and direction, can be studied at the micro- and/or meso-scales and provides insight into hourly wind changes across New Zealand. A modified FWI calculated using wind speed and VWC showed increased FWI_{mod} values in locations of complex terrain and terrain-driven winds, providing increased weighting for the role of wind speed variability in fire danger. When combined with the FWI metric, VWC could provide additional information for evaluating extreme fire weather and danger of unpredictable fire behaviour in locations subject to frequent wind changes. Future directions in this work could combine VWC with other fire prediction indices and other factors important for extreme fire behaviour.

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Data availability. Data used in this project, including the 4 km WRF simulation, FENZ station data, gridded FWI and modified FWI are available through the New Zealand Modelling Consortium (https://www.envlib.org/).

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