A Meteorological Study of the Port Hills Fire, Christchurch, New Zealand

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ABSTRACT

In February 2017, a wildfire occurred in the Port Hills on the southern boundary of Christchurch city in New Zealand. It was one of the country's most severe fires of the last decade in terms of the scale of evacuation, infrastructure damage, and property loss. On the third day of the fire, fire behavior was unexpectedly active, and two rapid downhill fire-spread events took place, creating a dangerous situation for firefighters. The aim of this paper is to explore the atmospheric processes that influenced the fire behavior at a range of meteorological scales, from the synoptic to meso- and microscales. Meteorological and fire data analyzed include observed data together with model simulations of weather conditions at different scales: 1) the Weather Research and Forecasting (WRF) numerical weather prediction model, which provided the regional context of the fire; and 2) the California Meteorological (CALMET) diagnostic model, which was used to undertake a higher-resolution investigation of atmospheric processes near the fire. Results indicate that the fire was not strongly seasonally influenced. Instead, it appears the fire conditions were the effect of a specific combination of synoptic weather conditions and local meteorological conditions. The first rapid downhill fire-spread event was the result of airflow interaction with the intricate terrain of the Port Hills under stable nocturnal conditions. The second downhill fire-spread event bears similarities to vorticity-driven lateral spread, because the downhill component of the spread happened on a broad fire flank perpendicular to the surface wind direction and characteristic pyrocumulus convection occurred.

1. Introduction

Two fires started on 13 February 2017 in hilly terrain along the southern border of Christchurch city in the

Canterbury region of New Zealand; they combined into one fire on 15 February. These fires are known collectively as the Port Hills fire. The proximity of the fire to a large urban center (Christchurch) meant that the fire was record-breaking for New Zealand in terms of property loss, the threat to infrastructure, scale of evacuation, and smoke impact on the urban population. On 15 February (the third day of fire activity), as well as combining into a single blaze, the fire exhibited unusual behavior, including fast downhill fire spread on two separate occasions and

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highly active fire behavior evidenced by the formation of a large pyrocumulus plume. Fast downhill fire spread poses a risk to the safety of firefighters as it is generally assumed that fires spread faster uphill than downhill. Firefighting often takes place downhill from a fire in complex terrain, as it is considered safer. Rapid downhill fire runs can therefore take firefighters by surprise and put them in danger.

The aim of this study is to understand the influence of atmospheric processes operating at different time and space scales on the evolution and behavior of the Port Hills fire. Meteorological conditions have a major influence on fire behavior, which makes understanding their effect critical to improving our ability to predict fire behavior. In this regard, it is important to consider a range of temporal and spatial scales of meteorological effects, because their influence on fire behavior takes place at the climatological time scale (e.g., Jolly et al. 2015; Littell et al. 2009), synoptic weather scale (e.g., Schroeder et al. 1964), and the smaller meso- and micro-scales (e.g., Sharples 2009), as described in the following paragraphs.

a. Atmospheric processes and fire

Deviations from long-term climate conditions can influence fuel moisture content and thus the fuel load available for consumption by the fire (Westerling et al. 2003). Previous research has identified relationships between longer-term climate signals, such as the Pacific decadal oscillation and El Niño–Southern Oscillation, and wildfire occurrence in different parts of the world (e.g., Macias Fauria and Johnson 2008). Previous research has also shown that climatic conditions associated with the occurrence of wildland fires include the following (Brown et al. 2008; Marlon et al. 2012):

- relationships between temperature and rainfall that drive biomass production, contributing to the buildup of fuel over several months or years;
- the effect of drought periods on drying fuel, making it more conducive to the ignition and spread of fires and increasing the fuel load.

Synoptic-scale weather systems can influence temperature, relative humidity, and wind during the days leading up to fires as well as during fire periods, thereby influencing fire-spread rates and behavior. Brotak and Reifsnyder (1977) suggested that the passage of dry cold fronts and high pressure systems that bring warm and dry conditions are important surface synoptic weather patterns associated with major wildfires. A number of large fires have either taken place following a dry cold frontal passage or prior to a cold front passing when strong, warm, and gusty winds are

common (Schroeder et al. 1964; Engel et al. 2013; Ma et al. 2010).

Mesoscale atmospheric processes often contribute to sudden changes in fire behavior, putting firefighters at risk. They frequently involve the interaction of the prevailing wind with the underlying terrain, and sometimes include the effect of the fire itself. The Canterbury region in New Zealand is prone to foehn winds that frequently manifest as a mesoscale feature. These winds occur when synoptic-scale westerly winds descend the lee slopes of the Southern Alps (Sturman and Tapper 2006; Macara 2014), causing warm, dry, and windy conditions. Several major New Zealand fires were associated with foehn winds that occurred prior to dry cold fronts. Examples include the Tikokino fire in Hawkes Bay in January 1991 (Rasmussen and Fogarty 1997), the Berwick Forest fire in Southern Otago in February 1995 (Rasmussen and Fogarty 1997), and the Bucklands Crossing fire of March 1998 in North Otago (Pearce et al. 2004). Foehn winds were also associated with the occurrence of large fires in other parts of the world, including California and southeastern Australia (Sharples et al. 2010; Westerling et al. 2004).

Microscale meteorological phenomena that develop in areas of complex terrain may also play an important role in fire risk, behavior, and spread (Linn et al. 2007). Changes in wind speed and direction can lead to rapid changes in the direction and rate of fire spread, as well as the intensity of fires (Sharples et al. 2012), which is a major concern for firefighter safety. The complexity of surface terrain can result in dynamic changes in fire behavior such as vorticity-driven lateral spread (Simpson et al. 2016; Sharples et al. 2012). This occurs in response to fire-induced vorticity on the fire's flanks in the immediate lee of a ridge line (Sharples et al. 2013). In this case, the laterally advancing fire flanks may subsequently become the dominant contributors to extreme pyroconvection and fire spread (Simpson et al. 2014). This type of fire behavior results in a transition from a normal frontal burning pattern to a spread pattern over a wide area dominated by rapid lateral spread (spread in a direction roughly perpendicular to the ambient wind direction) (McRae et al. 2015).

The influence of the meteorological scales on the Port Hills fire are investigated in the subsequent sections. A description of the fire environment and fire progression is given in section 1b. Methods used are discussed in section 2, results are presented in section 3, and the two rapid downhill spread events are discussed in section 4.

b. Description of the fire

The Port Hills fire occurred on the southern boundary of Christchurch city and resulted in the loss of nine

FIG. 1. (a) The location of the Port Hills fire footprint within New Zealand, and the proximity of the fire to Christchurch city. The two points of ignition are represented by the red dots labeled EV (Early Valley) and MH (Marley Hill). (b) A terrain map of the Port Hills showing variations in altitude (source: Land Information New Zealand 8-m Digital Elevation Model, 2012; <https://data.linz.govt.nz/layer/51768-nz-8m-digital-elevation-model-2012/>). (c) Fuel types consumed by the Port Hills fire (source: Landcare Research, Land Cover Database v4.1; <https://iris.scinfo.org.nz/layer/48423-lcdb-v41-land-cover-database-version-41-mainland-new-zealand/>).

houses with damage to a further five, as well as damage to roads, a mountain-bike adventure park, forestry blocks, recreational tracks, and nearby farmland (total cost estimated at > NZD\$25 million). It also threatened power lines, an aviation radar, and communications networks. Two fires, named the Early Valley and Marley Hill fires, started during the late afternoon on 13 February 2017 and merged on 15 February 2017, with the main fire activity lasting until the early morning of 16 February 2017. The combined fires

(collectively referred to as the Port Hills fire) covered a total area of 1661 ha (4104 acres), with a final perimeter of 61 km (outlined area in Fig. 1a). It took 66 days to completely extinguish the fire.

The Port Hills are hilly terrain features that form part of an extinct volcano, with ridges and peaks between 300 and 500 m above mean sea level. The fire occurred in an area of moderate to steep slopes and ridges (with inclinations between 10° and 40°), in neighboring valleys running approximately northwest to southeast (Fig. 1b).

FIG. 2. (a) The progression of the Port Hills fire on 14–16 Feb 2017, shown as isochrones indicated by different hatched patterns. Two separate rapid downhill fire-spread events are depicted by labels “X” and “Y” and the associated arrows that show direction of fire travel. The two points of ignition are represented by the red dots. The gondola line is represented as a thick black line. The key indicates the fire spread in consecutive time periods up to the time and day indicated. (b) A three-dimensional view of the fire progression, illustrating the two rapid downhill fire-spread events X, circled in red, and Y, circled in blue.

The fuel types of the Port Hills fire included well-cured, 80%–100% dead, grass fuels interspersed with gorse scrub, pine plantations, and regenerating native scrub and forest (Fig. 1c). The native forest was less flammable and mostly aided fire suppression efforts. Most of the patches of gorse scrub had been sprayed for weed control, were recently dead, and thus contributed significantly to fire spread and intensity (Pearce 2018).

An outline of the entire fire chronology was provided by Pearce (2018) and in the Fire Emergency New Zealand after-action review by the Australasian Fire and Emergency Service Authorities Council (2017). In contrast, this paper investigates meteorological conditions solely in regard to the third day of fire activity (15 February), on which the most active and unusual fire behavior occurred (Fig. 2). Two separate rapid downhill fire-spread events took place on this day (events X and Y;

Fig. 2a with a three-dimensional view in Fig. 2b). It was also on this day that the two fires merged and active “blowup” conditions occurred, resulting in unexpected fire escalation (McRae et al. 2015). The meteorological conditions during the rapid downhill fire-spread events and active fire behavior are the focus of this study. Throughout the text, times are indicated in New Zealand standard time (NZST), which is universal coordinated time (UTC) + 12 h.

On the morning of Wednesday 15 February 2017, the Early Valley fire made a rapid downhill fire run toward properties on the eastern slopes of the Port Hills, overlooking Lyttelton Harbour, as well as toward the north-northeast (indicated by the red arrows next to the label “X” in Fig. 2a). The downhill nocturnal fire-spread rate was unusually fast (approximately 800 m in 2–3 h down slopes inclined at 20°–40°). According to witnesses, this fire spread occurred between approximately 0300 and 0600 NZST. The fire isochrones were only recorded later, at 1030 NZST (indicated in Fig. 2a). This downhill fire spread resulted in urgent evacuations of communities located at the base of the hills near Lyttelton Harbour.

Between about 1030 and 1300 NZST the same day, a series of spot fires ignited in a pine forest underneath a burning gondola (black line, Fig. 2a) that had been left operating in the adventure park below Marley Hill. These spot fires quickly grew and spread (as indicated by the blue arrow associated with the label “Y” in Fig. 2a) under a developing northeasterly-to-easterly wind (a sea breeze) at an estimated spread rate of 3.5 km h^{-1} (Pearce 2018) and laterally downwind in the direction of Christchurch city (purple arrows associated with label “Y” in Fig. 2a). The Early Valley and Marley Hill fires merged between 1030 and 1300, at which point the fire covered >400 ha. Around 1300 NZST, pyrocumulus convection started to develop above the fire, which lasted for approximately 3–4 h. During the afternoon, the fire was extremely active and continued spreading toward the west as well as laterally, in a downslope direction toward Christchurch city, covering another 500 ha between 1300 and 1700 NZST. Several instances of spotting were witnessed during this time. During the night of 15 February fire activity slowed, with the burnt area growing by approximately 200 ha overnight.

2. Methods

a. Observational data analysis

1) CLIMATIC CONDITIONS

Observations of temperature, relative humidity, and precipitation were obtained as long-term values (30-yr averages/totals for 1987–2017) for the month of

February, average/total values for February 2017, and daily averages/totals for the three days leading up to the fires and during the three days of main fire activity. These data were collected at the Christchurch Airport weather station, operated by the New Zealand Meteorological Service (MetService) and located approximately 14 km north-northwest of the fire (location A in Fig. 3). These data were analyzed to assess whether the month in which the fire took place and/or the fire days had anomalous weather.

2) SYNOPTIC CONDITIONS

Data obtained included mean sea level pressure analysis charts from the MetService and values of 500-hPa height and wind from the U.S. National Centers for Environmental Prediction (NCEP) operational analysis dataset. These data were used to ascertain the prevailing synoptic conditions leading up to and during the fire.

b. Numerical modeling

1) MODELS USED

To provide a more comprehensive four-dimensional (space and time) perspective of the meso- and micro-scale weather conditions prevailing during the Port Hills fire than that available from observations alone, the observational data were complemented by the outputs from an atmospheric model, the Advanced Research Weather Research and Forecasting (WRF) Model, version 3.8 (Skamarock et al. 2008). Simulation results were dynamically downscaled by means of a sequence of nested grids with grid spacings of 27, 9, and 3 km (Fig. 3). Further downscaling to 150 m spacing was achieved using the California Meteorological (CALMET) diagnostic model (Scire et al. 2000).

The WRF Model is an advanced, physics-based, four-dimensional, numerical weather model, and the main physics schemes used in the simulation are summarized in Table 1. The vertical configuration consisted of 33 pressure levels extending from 1000 to 21 hPa (from the ground surface to approximately 23 km in altitude). The outer domain was nudged at its lateral boundaries every 24 h with NCEP Final Analysis (FNL) data.

The CALMET model was used to downscale the WRF 3-km output grid to 150 m grid spacing by means of a diagnostic wind field module. This allowed objective analysis and parameterized treatment of slope flows, kinematic terrain effects, and terrain blocking effects. CALMET also makes use of a micrometeorological model based on the energy budget method of Holtslag and Van Ulden (1983) for an overland boundary layer and a profile scheme for the overwater boundary. The CALMET modeling domain was 40 km by 40 km, centered

FIG. 3. (left) The WRF nested modeling domains, with horizontal grid spacings of 27 (d01), 9 (d02), and 3 (d03) km, and the CALMET 150-m grid spacing domain (d04) shown as the smallest black-outlined square. (right) The CALMET modeling domain, showing the footprint of the Port Hills fire in black. Yellow dots (labeled A, B, and C) are those used to evaluate CALMET, and red dots (labeled D, E, and F) indicate the locations of surface weather stations used as nudging input in CALMET. The green dot (labeled P) indicates the location north of the fire area where upper-air data were extracted from the model output. Stations labeled A, F, and G were used to calculate components of the New Zealand Fire Danger Rating System. Location A is where Christchurch Airport is located and where upper-air data were obtained.

over the fire footprint (Fig. 3) with 11 vertical layers ranging between 20 and 4000 m, positioned at a vertically increasing grid spacing. The WRF wind fields were used as an initial guess in CALMET and were supplemented and nudged with observational data from three surface weather stations (see Fig. 3 for locations). The terrain data used in CALMET were the 30-m-resolution Shuttle Radar Topography Mission data (Farr et al. 2007), and the New Zealand Land Cover Database, version 2 (Thompson et al. 2003), was used as land surface input.

2) MODEL EVALUATION

CALMET surface fields were evaluated against observations from three weather stations A, B, and C

(Fig. 3). The CALMET model was nudged with observations from weather stations D, E, and F (Fig. 3). Stations A and C are operated by the MetService; stations B, D, and E are operated by the National Institute for Water and Atmospheric Research (NIWA); and station F is operated by Fire and Emergency New Zealand. Stations A, B, D, E, and F have 10-m masts, whereas station C is located on the top of the Port Hills (494 m above mean sea level) on a broadcasting mast at a height of 120 m above the ground. All of these surface stations are regularly calibrated, and they are data quality assured by their respective operators.

Modeled upper-level wind fields from CALMET were compared with observations collected by aircraft as they landed at or took off from Christchurch Airport.

TABLE 1. Physics schemes used in the WRF Model runs.

	Scheme used	Source
Microphysics	Kessler	(Kessler 1995)
Longwave radiation	Rapid Radiative Transfer Model	(Mlawer et al. 1997)
Shortwave radiation	Dudhia	(Dudhia 1989)
Surface layer	Monin–Obukhov	(Janjić 1994)
Land surface scheme	Noah land surface model with four soil layers	(Ek 2003)
Boundary layer scheme	Yonsei University	(Hong et al. 2006)
Cumulus parameterization	Updated Kain–Fritsch scheme (domains 1 and 2 only)	(Kain 2004)

Photographs of directional wind shear within the smoke column on 15 February were also used as a qualitative indication of the validity of the CALMET wind profile.

3) FROUDE NUMBER ANALYSIS

Froude numbers were computed using modeled data from CALMET from a ridgetop location above Lyttelton Harbour, near downhill fire-spread event X (Fig. 2). The Froude number is a nondimensional value that is the ratio of inertial forces to gravitational forces and is defined as $F = U/(Nh)$ (Wooldridge et al. 1987; Barry 2008), where h is the height of an obstacle to the airflow and U is the mean wind speed through the approaching layer between the ground level and the height h , at a distance greater than $5h$ upstream of the hill; N is the Brunt–Väisälä frequency of the upstream flow, which is an indicator of atmospheric stability and is defined as $N^2 = (g\theta)(d\theta/dz)$ (Wooldridge et al. 1987), where g is gravitational acceleration, θ is potential temperature, and z is height above the surface. When $F < 1$, vertical motion is suppressed below a critical height $H_c = h(1 - F)$ but flows smoothly over the hill above this height (Snyder et al. 1985), remaining attached to the terrain below as it proceeds downhill.

3. Results

Model results and observations were used to investigate potential causes of the active fire behavior exhibited on 15 February, as described in the following sections. Model performance was evaluated against observation data before using the model data to extend the observations and make meteorological interpretations.

a. Climate

1) COMPARISON WITH 30-YR AVERAGES

Average temperature, relative humidity, and total precipitation for February 2017 were compared with 30-yr averages for February to identify whether anomalous weather took place during the month when the fire occurred (February), three days prior to the fire, and the three days of the fire (Table 2). Relative to the 30-yr averages for February, in February 2017

- 1) *temperatures* were very similar to the long-term average (within 1°C),
- 2) *relative humidity* was 8% lower than the long-term average of 80%,
- 3) *precipitation frequency* (the number of days per month with precipitation equal to or greater than 1 mm) was the same as the climatic average for February (but no precipitation occurred from 2 February 2017 until the latter half of February 2017, after the fire), and

TABLE 2. A summary of 30-yr-averaged climatic conditions for February compared with February 2017 and the three days prior to and during the fire event. Daytime was assumed to be from 0700 to 1800 NZST, and nighttime was assumed to be from 1900 to 0600 NZST the following day. Data were obtained from the Christchurch Airport weather station, shown at location “A” in Fig. 3.

Variable	30-yr avg for Feb	Feb 2017 avg	Three days prior to fire (10–12 Feb)	Fire days (13–15 Feb)
Daily avg air temperature (°C)	16.8	16.7	13.7, 15.0, and 19.0	16.3, 18.4, and 14.3
Daily max air temperature (°C)	22.1	22.5	20.7, 21.3, and 28.5	23.8, 24.4, and 22.7
Daily min air temperature (°C)	11.6	11.0	6.5, 6.4, and 13.3	10.2, 13.0, and 3.1
Relative humidity (%)	80	72	69, 77, and 67	62, 34, and 50
Precipitation frequency (days/month with 1 mm or more)	5	64 (day) 81 (night) 5	54, 63, and 47 (day) 74, 91, and 87 (night)	57, 26, and 35 (day) 82, 43, and 49 (night)
Total precipitation (mm)	40.1	20.0	0	0

FIG. 4. Mean sea level pressure analysis maps for (a) 0000 UTC (1200 NZST) 13 Feb 2017, (b) 0000 UTC (1200 NZST) 14 Feb 2017, and (c) 0000 UTC (1200 NZST) 15 Feb 2017 (source: MetService of New Zealand).

- 4) *precipitation* in February was one-half that of the climatological average.

Temperature, relative humidity, and precipitation during the period 10–12 February, prior to the fire, were compared with 30-yr averages for the month of February:

- 1) average, maximum, and minimum *temperatures* were lower on 10 and 11 February relative to the 30-yr averages and on 12 February (the day before the fire started) average, maximum, and minimum

FIG. 5. Maps of mean 24-h 500-hPa geopotential heights for: (a) 13, (b) 14, and (c) 15 Feb 2017 (source: <https://www.esrl.noaa.gov/psd/data/histdata/>).

temperatures were 2.2°, 6.4°, and 1.7°C higher than the 30-yr averages,

- 2) *relative humidity* was low and decreased to a level that was 13% lower than the 30-yr average on 12 February, and
- 3) *precipitation* did not occur on these days.

During the three days of active fire, temperature, relative humidity, and precipitation relative to the 30-yr averages for the month of February were as follows:

- 1) *temperature* was relatively similar (within 2.5°C) and did not vary notably from that situation except for a 3.1°C minimum temperature on 15 February,

FIG. 6. The effect of wind shear and a temperature inversion evidenced by the directional change in the fire plume from a northeasterly direction near the surface to northwesterly flow aloft. This photograph was taken at 1500 NZST 15 Feb by the Christchurch Airport meteorological “webcam,” located at position A in Fig. 3 (provided by the MetService).

which was well below the 30-yr average minimum of 11.0°C,

- 2) *relative humidity* was well below (18%, 46%, and 30%) the climate average and on 14 and 15 February Christchurch did not experience the usual moist nighttime conditions that would have reduced normal overnight moisture resorption by fine fuels (the values in Table 2 are considered to be low for the region), and
- 3) *precipitation* did not occur on these days.

2) SEASON

There were no large deviations from the 30-yr averages of temperature, humidity (all values within 10% of 30-yr averages for the month in question), or rainfall (rainfall was either higher or within 5% of the 30-yr average for the month) as based on the data available from the national climate archives for the three months prior to the fire (November and December 2016 and January 2017 data held by the National Institute for Water and Atmospheric Research, not shown). These data indicated that there was no strong seasonal influence on the fire.

The fire weather index (FWI) value from the New Zealand Fire Danger Rating System (Anderson 2005) was calculated for weather stations A, F, and G (Fig. 3) and averaged to obtain a single near-fire value for 14 and 15 February. The FWI is a measure of the potential fire

intensity of a spreading fire and incorporates seasonal data through calculation of fuel moisture codes. During the fire the FWI ranged from high to extreme with values of 24 on 13 February and 44 and 38 on the following two days. We note that, for New Zealand, an FWI value between 21 and 29 is considered very high and values higher than 30 are extreme (Pearce 2018). The elevated FWI values on 14 and 15 February are the result of the combined effect of low relative humidity, high wind speeds, and a 20-day period without rain immediately before the fire (Pearce 2018).

b. Synoptic conditions

1) LOWER ATMOSPHERE

The lower-than-average relative humidity preceding the fire was associated with a dry cold front passing over the Canterbury region on 12 February. Strong westerly and northwesterly flows that developed in association with this approaching cold front produced dry, windy, and warm conditions over Canterbury as a result of the foehn effect of the Southern Alps.

Christchurch is situated in the westerly wind belt, and, at times, a continental high pressure system that formed over Australia can cross the Tasman Sea relatively unaltered, resulting in warm and dry spells in New Zealand. Prior

FIG. 7. Time series of modeled (Mod; red) and observed (Obs; blue) temperature ($^{\circ}\text{C}$, solid lines) and relative humidity (%; dashed lines) at stations (top) A, (middle) B, and (bottom) C. Locations of the stations are indicated in Fig. 3.

to the Port Hills fire, record-breaking high temperatures were recorded in Victoria and New South Wales, Australia (Australian Associated Press 2017; Australian Broadcasting Corporation 2017). This unusually hot weather was caused by a weak prefrontal, northwesterly airflow associated with a high pressure system located over the northern Tasman Sea. This high pressure system moved northeast of New Zealand prior to the fire (Fig. 4a) and remained as a stationary high for the duration of the fire. This resulted in advection of warm and dry air and northwesterly flow in the Canterbury region, which typically overlays the shallow layer of maritime air over the Tasman Sea.

By 14 February (Fig. 4b), the second day of the fire, a second high pressure system from Australia started to move over the Tasman Sea to the west of New Zealand. This, along with the stationary high to the northeast, resulted in several days of westerly flow over the South Island leading to foehn conditions in Canterbury. This high pressure system moved closer to the South Island on 15 February (Fig. 4c), the day of significant fire spread. The lack of cloud cover and weaker synoptic winds associated with this anticyclone were responsible for strong radiative cooling in the early hours of 15 February, resulting in below-normal minimum temperatures (3.1°C ;

Table 2). Local deformation of the isobars over the South Island under westerly airflow, as shown in Fig. 4c, is a very common occurrence. It is caused by the interaction of the flow with the Southern Alps, which can create a leeside trough along the east coast (Sturman and Tapper 2006). The synoptic wind direction on this day was a disturbed westerly, which continued the dry and warm foehn conditions, until the development of a local easterly sea breeze, which began just before noon and penetrated below the overlying westerly flow (a common local phenomenon, especially in summer).

The Haines index is a measure of the risk of a dry, unstable atmosphere causing erratic fire spread and growth (Winkler et al. 2005; Haines 1988) and ranges from 2 (very low risk) to 6 (very high risk). The Haines index was low on 13 February and was very high and high on 14 and 15 February, respectively.

2) UPPER ATMOSPHERE

An upper-level trough was present over the Tasman Sea, west of the South Island at the start of the fire (Fig. 5a). The location of such troughs relative to the fire area may be related to the development of some large fires (Brotak and Reifsnyder 1977; Mills 2005; Kaplan et al. 2008; Potter 2012). The winds at this level were

FIG. 8. Time series of modeled (Mod; red) and observed (Obs; blue) wind speed and direction at stations (top) A, (middle) B, and (bottom) C. Locations of the stations are indicated in Fig. 3.

dominated by northwesterly flow that declined in intensity from 13 to 15 February. As the slow-moving trough decayed, it fractured (Sturman and Tapper 2006), with the southern section moving eastward while the subtropical section remained largely stationary (Figs. 5a–c). By 15 February, as the surface high pressure moved across the Tasman Sea toward the South Island, a confluent airflow structure developed at 500 hPa over New Zealand (Fig. 5c). As Sturman and Tapper (2006) have suggested, these weather patterns often contribute to descending motion, leading to development of subsidence inversions over New Zealand. These patterns have previously affected the structure of pyrocumulus clouds in the region in a similar way to the Port Hills fire smoke plume pictured in Fig. 6 (Sturman 1980).

c. CALMET evaluation

1) SURFACE OBSERVATIONS

CALMET model results for 15 February were compared to observations and showed similar trends for

temperature, relative humidity and wind speed (Figs. 7 and 8). CALMET overpredicted relative humidity at the station located 120 m above the ground (station C) between 0000 and 0800 NZST. The observed humidity was low for this region. As expected, greater agreement exists between predicted and observed wind speeds for station A, situated on flat terrain (although wind speeds were underpredicted from 1200 NZST onward) than for stations B and C, which are situated in the complex terrain of the Port Hills. There is general agreement between modeled and observed wind direction (Fig. 8), with observed and predicted directional changes occurring at similar times. All data, observed and modeled for all stations, showed a change in wind direction to the land–sea breeze around 1100 NZST.

2) UPPER-LEVEL WINDS

There is general agreement between modeled and observed winds (obtained from aircraft measurements), between the surface and 2.5 km above ground, at 1200

FIG. 9. A comparison between vertical profiles of observed (blue arrows) and CALMET-modeled (red arrows) wind speed and direction at Christchurch Airport for 1200 and 1800 NZST 15 Feb.

and 1800 NZST 15 February at Christchurch Airport (Fig. 9). These wind measurements indicate the formation of a low-level jet (LLJ) between 1200 and 1900 NZST 15 February, embedded within the northeasterly sea-breeze layer and capped by a northwest flow resulting in directional shear between the LLJ and the overlying synoptic airflow (Figs. 6 and 9).

In this part of New Zealand, sea breezes are often capped by such shear zones, as the prevailing winds above are generally from the opposite direction (i.e., from the west; Sturman and Tyson 1981; McKendry et al. 1986, 1987). They are also typically associated with capping temperature inversions, as they comprise a cold slab of marine air undercutting air that has been warmed by passage over the mountains and land areas of the central South Island, and are often associated with the foehn effect (Kossmann and Sturman 2003; Sturman and Tapper 2006).

A photograph (supported by video footage) of a pyrocumulus cloud and smoke plume generated by the fire was taken at Christchurch airport at 1500 NZST 15 February (Fig. 6). It shows the significant wind shear evident at around 800–1500 m above mean sea level (MSL) within the fire plume, as supported by the vertical profiles of wind shown in Fig. 9. The photo shows plume movement toward the west-southwest in the near-surface layer (up to about 800 m MSL) and toward the east in the layer above what appears to be a zone of maximum horizontal spread of smoke.

The sheared flow shown by the smoke from the fire serves as an ideal model evaluation opportunity. CALMET simulated the surface northeasterly winds, typical of sea-breeze development over the Christchurch area (as previously described by Sturman and Tyson 1981; McKendry et al. 1986, 1987; Sturman and Tapper 2006) and the resulting wind shear with the westerly upper-level winds (Fig. 10).

4. Discussion

There were two rapid downhill fire-spread events, and in this section we explore the possible meteorological influences that are believed to have caused or strengthened these events. Event X occurred between 0300 and 0600 NZST, and event Y occurred between 1030 and 1730 NZST 15 February. Figure 2 shows where these events occurred relative to the terrain of the Port Hills.

a. Downhill fire-spread event X

As discussed in section 3b(1), the synoptic conditions on 15 February were characterized by the high pressure system that moved over New Zealand leading to a continuation of weak westerly foehn winds (Fig. 4c). The foehn winds brought about exceptionally dry conditions and Christchurch did not experience its usual moist nighttime conditions (Table 2). This would have reduced overnight moisture resorption by fuels (McRae et al. 2015). This event occurred on an exceptionally cold

FIG. 10. CALMET-modeled wind fields (winds at every fifth model grid point are shown) over the Christchurch and Port Hills region at 1500 NZST 15 Feb. Black arrows indicate surface (10 m) winds, and gray arrows represent upper-air (1500 m) winds. The location of the Christchurch Airport webcam is indicated by a blue symbol (top left), and the fire footprint is shown in yellow.

morning and is associated with northwesterly-to-west-northwesterly flow aloft and southwesterly-to-westerly flow at the surface, under stable anticyclonic conditions, as indicated by an elevated temperature inversion (Fig. 11). Unusually fast nocturnal downhill fire spread was reported by crews battling the fire and evacuations were put in place for areas near the township of Governors Bay, located at the base of the hill close to Lyttelton Harbour (Pearce 2018).

The Froude number F was investigated to explore conditions that may have led to this fast-downhill fire spread. The Froude number indicates if airflow is attached to the hill/terrain as it moves over and to the lee of the hill. For $F < 1$, vertical motion is suppressed below a critical height and airflow moves around the hill below this height, but flows smoothly over the hill above this height, in an attached manner (Snyder et al. 1985). A low value for F ($F < 1$) indicates that flow would remain attached, rather than forming a separation eddy on the lee side of a ridge. It is believed that attached flow over the terrain led to the rapid downhill fire spread observed by fire crews.

Froude numbers were computed using the CALMET model data for the ridge above Lyttelton Harbour ($h = 505$ m, see Fig. 2), where the fire crested the ridgeline

from the western side of the hills. The Froude numbers ranged from 0.35 to 0.68 over the duration of the documented fast downhill fire spread. The critical height, the height above which flow adheres to the surface and moves smoothly over the hill with little to no flow separation on the lee side of the hill (Carruthers and Hunt 1990), was computed to range between 160 and 330 m MSL. These computed critical heights are lower than the 505-m ridge and therefore indicative of attached flow at greater heights. These values suggest that the combination of local atmospheric stability and terrain height resulted in attached flow that drove unusually rapid downhill fire spread in this instance.

The flow attached to the terrain pushed the base of the flames downhill, while the buoyant flames resulting from locally burnt fuel were unable to counter the downslope propagation. Byram's convection number (describing the ratio of the buoyancy force of the plume to the inertial force due to wind) could be used to provide greater insight into the relationship between wind effects and plume buoyancy in cases where the data are available (Morvan and Frangieh 2018). In this study, we do not have sufficient data regarding fire intensity and rate of spread to compute Byram's convection number.

FIG. 11. Skew T -log p diagram derived from WRF Model data at 0600 NZST 15 Feb, for a profile at point P, indicated in Fig. 3.

The Froude numbers' indication of attached flow accords with observations of smoke and cloud hugging the Port Hills terrain that are shown in the photograph taken from the Christchurch Airport at 0600 NZST 15 February (Fig. 12). These results suggest that Froude numbers may be of value for firefighters as an operational indicator of potential for unusually rapid downhill fire spread in stable atmospheric conditions.

b. Downhill fire-spread event Y

The second rapid downhill fire-spread event occurred on 15 February between 1030 and 1700 NZST. During this period, a low-level sea breeze developed underneath the overlying relatively warm westerly flow. This led to the formation of an elevated temperature inversion capping an LLJ (within the sea-breeze layer), as indicated by aircraft measurements of wind speed (Fig. 9). Stable conditions remained aloft, as is evident from the lack of significant vertical development shown in the photograph of the pyrocumulus cloud in Fig. 6 (i.e., no cumulonimbus development occurred) and the thickness of the stable layer shown in Fig. 11 (between the 780 and 600 hPa pressure levels). Past studies have associated LLJ wind profiles as contributing to active

fire behavior and blow-up conditions (i.e., Byram 1954; Goens 1990; Charney et al. 2003). There are two explanations for this: 1) the decrease in wind speed with height (negative wind shear) above LLJs allows a convective column to develop above the fire (Brotak 1992; Simpson et al. 2013) and 2) momentum from the LLJ can be mixed down to the surface, causing accelerated rates of spread (Charney et al. 2003). Between 1030 and 1300 NZST the two individual fires merged at the same time as an additional ignition source (a running chairlift) started spot fires along the slope of the hills. Previous studies have associated junction fires (the merging of two individual fires at an oblique angle) with active and dynamic fire behavior (fire behavior where rate of spread cannot be determined solely from the fire environment) (Raposo et al. 2018; Thomas et al. 2017). Later, between 1300 and 1700 NZST, a large pyrocumulus cloud formed above the fire, signaling highly active behavior (Fig. 6).

During event Y (from roughly 1030 to 1700 NZST) rapid fire spread simultaneously occurred in two directions: 1) following the contours of the topography, pushed by the sea breeze westward, and 2) downhill, in a direction perpendicular to the near-surface wind direction toward the suburbs of Christchurch city (lateral spread).

FIG. 12. Smoke and cloud hugging terrain under stable nocturnal conditions. This photograph was taken at 0600 NZST 15 Feb by the Christchurch Airport (location A; Fig. 3) meteorological webcam (provided by the MetService).

The downhill component of the fire spread occurred on a broad, rapidly advancing fire flank and covered around 500 ha in the seven hours between 1030 and 1700 NZST.

The rapid lateral downhill fire spread during this event bears similarities to “fire channeling,” later termed vorticity-driven lateral spread (Simpson et al. 2014), an example of dynamic fire behavior. This type of fire behavior marks a transition from a normal frontal burning pattern to a burning pattern over a wide area, associated with a rapidly advancing fire flank (in a direction perpendicular to the prevailing wind), downwind extension of the flaming zone and constraining of the upwind edge of the flaming zone by a major break in the topographic slope (Sharples et al. 2012).

The typical conditions under which vorticity-driven lateral spread may occur were investigated in relation to several fires near Canberra by Sharples et al. (2012), and broadly supported by the theoretical modeling work of Simpson et al. (2016). Some of the characteristic features of vorticity-driven lateral spread were present in the Port Hills fire event. The near-surface wind direction was roughly perpendicular to the ridges and valleys of the Port Hills (gray arrows in Fig. 13). The terrain slopes (Leathwick et al. 2002), extracted from a 25-m DEM to identify slopes that would be perceived by a person in the landscape at a scale of 10 m using the scaling formula of McRae (1997), were sufficiently steep (greater than $\sim 20^\circ$ – 26°) (as shown in Fig. 13). The modeled surface

wind speeds at a location close to the fire area (location P in Fig. 3) increased from 0.5 to 6 m s^{-1} during the period of active behavior, such that wind speeds were sufficient for vorticity-driven lateral spread to occur. Large-scale pyrocumulus convection as a consequence of this type of fire behavior (McRae et al. 2015) also occurred (Fig. 6).

5. Summary

The February 2017 Port Hills fire was one of the most severe fires in New Zealand in the last decade in terms of the scale of evacuation, infrastructure damage, and property loss. The fire displayed notable behavior in terms of rapid fire escalation and rates of spread, including two rapid downhill fire-spread events. Rapid downhill fire runs are especially dangerous for firefighters because it is usually assumed that fires spread slower downhill and therefore rapid downhill runs can take firefighters by surprise. This research contributes to a broader understanding of how meteorological conditions influence fires and circumstances under which rapid downhill fire spread can occur.

For the Port Hills fire, the hot, dry conditions for brief periods prior to and during the fire were driven by synoptic weather systems, including the passage of a dry cold front a day before the fire started, which resulted in a foehn wind descending from the Southern Alps. The foehn wind was warm and dry, readying the fine fuels

FIG. 13. Terrain slope ($^{\circ}$) as derived by Leathwick et al. (2002) (shown by color shading), and the CALMET-modeled wind field at 1500 NZST (gray arrows) when lateral (downhill) fire spread (in the direction of the large black arrow) occurred (within the approximate area circled in red). The progression of the Port Hills fire at different times on 15–16 Feb 2017 is indicated by different hatching.

and larger fuels for ignition. Examination of the weather for December–February in the lead-up to the fire shows no uncharacteristic seasonal influence on the fire or fuels. A disturbed westerly flow remained over the region during the fire days, which continued to produce dry foehn conditions in the presence of two prominent anticyclones positioned on either side of New Zealand.

Rapid downhill fire spread in event X resulted from airflow interaction with complex terrain under stable nocturnal conditions. Froude numbers calculated for the flow indicate attached flow as it moved into the lee of the hill, allowing the fire to spread smoothly and quickly downhill.

Rapid cross-slope and downhill fire spread in event Y occurred on a broad, rapidly advancing fire flank in a direction perpendicular (or lateral) to the prevailing surface wind direction. This event was associated with the onset of a sea breeze (easterly) under a disturbed westerly, that led to the development of a low-level jet that likely contributed to active fire behavior. During this event, the two separate fires merged into one, also contributing to active fire behavior. The lateral downhill fire spread bears similarities to vorticity-driven lateral spread. Terrain slopes and wind speeds were sufficient for vorticity-driven lateral spread to occur and a characteristic large pyrocumulus cloud developed above the fire ground.

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