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Some recent extreme wind events in New Zealand

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Abstract. Damaging winds, associated with a variety of weather phenomena, are frequently experienced in New Zealand. Observations and modelling of two recent extreme wind events; the Taranaki tornado outbreak of July 2007, and the Greymouth down-slope easterly wind storm of July 2008 are described in detail here. Post-event engineering damage surveys, rare for New Zealand, were done for these storms and the results are summarized here. Finally, the issue of sampling extreme wind events is raised and the need to include detailed numerical modelling analysis to understand wind gust climatologies at observing sites and extending these to wider regions is discussed.

Keywords: extreme winds; New Zealand; tornado; down-slope winds, lee-slope winds; wind damage; damage surveys.

1. Introduction

Due to New Zealand's mountainous terrain and mid-latitude location, severe and damaging winds are frequently experienced and associated with a range of weather phenomena such as; down-slope (or lee-slope) windstorms, thunderstorms and squall-lines, tornadoes, vigorous mid-latitude storms, and "ex"-tropical cyclones (warm core) that have transitioned to mid-latitude extra-tropical cyclones (cold core). The mid-latitude storms are responsible for the so-called "synoptic winds" and most of the 1-10 year return-period (RP) wind-gusts in New Zealand. However it is the other weather phenomena that have tended to produce the most notably damaging and longer RP wind events in New Zealand. Some of these noteworthy events were (i) the "Wahine" storm of April 10, 1968 which was associated with the ex-tropical cyclone "Giselle" and had recorded gusts of 75 ms^{-1} (Revell and Gorman 2003), (ii) the down-slope Canterbury windstorm of August 1, 1975, with recorded gusts up to 54 ms^{-1}, which caused widespread damage to 11,000 ha of forests (New 1989) and several buildings, (iii) the F2 Frankton (Hamilton) Tornado of August 25, 1948 which killed 3 and injured 80 people, and (iv) ex-cyclone Bola of March 7-8, 1988 which, apart from flooding, caused widespread wind damage especially to forests in the central North Island.

In this paper we describe modelling and observations of two recent and damaging New Zealand "non-synoptic" wind storms that had some unique features, the Taranaki tornado outbreak of July 5, 2007 and the Greymouth easterly storm of July 30, 2008. Results of a damage survey and numerical weather prediction model forecasts of the Taranaki tornadoes are covered in section 2. The third section covers the Greymouth wind storm and includes results from a damage survey and modelling

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of local terrain effects using a high-resolution computational fluid dynamics (CFD) model called GERRIS (Popinet (2003)). In the final section we discuss the Greymouth easterly-downslope windstorm in the context of the more commonly experienced northwesterly storms of Canterbury and discuss possible sampling problems for assessing wind gust climatologies in New Zealand.

2. Taranaki Tornado outbreak of July 5, 2007

New Zealand experiences on average about 7 tornadoes per year with the province of Taranaki (location shown in Fig. 1) getting about 1 per year (Burgess *et al.* 2007). Most are of the “cold season” variety similar to those of Australia (Hanstrum *et al.* 1998) and are associated with pre-frontal squall lines, i.e., bands of thunderstorms embedded in strong unstable pre-frontal northwesterly flow. These conditions were present on the evening of July 5 so a tornado occurrence would not have surprised forecasters. What would have surprised was the number and geographic extent of the tornadoes reported as this was an outbreak which had no historic precedent in New Zealand. Between 1720 and 1800 NZST, a large number of tornadoes, perhaps as many as twenty, ranging from EF0 to EF3 struck many different parts of the province (see Fig. 2). A state of emergency was declared in the New Plymouth District and temporary supplies and accommodation had to be found for affected residents. There were reports of minor, although not severe, injuries. At least 7,000 homes were left without electricity throughout the region, due to damaged power lines and lightning

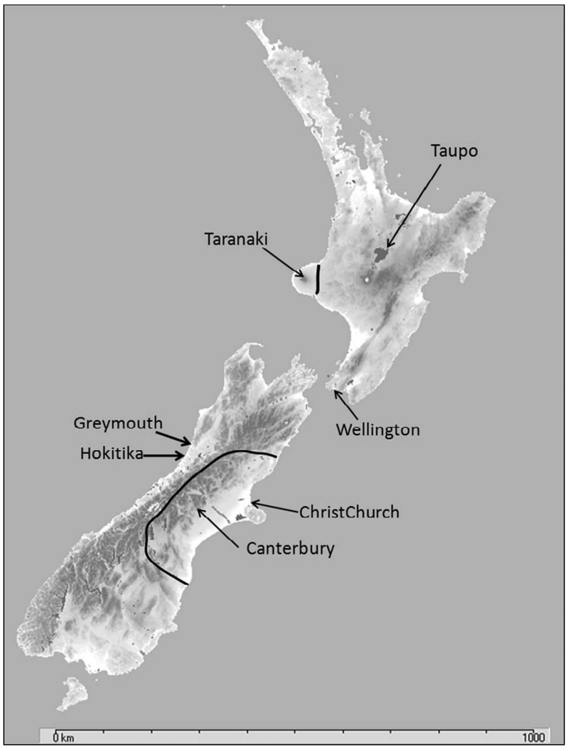

Fig. 1 Map of New Zealand showing locations mentioned in the text. The black lines approximate the regional boundaries of Taranaki and Canterbury. The gray-scale shaded relief indicates the terrain

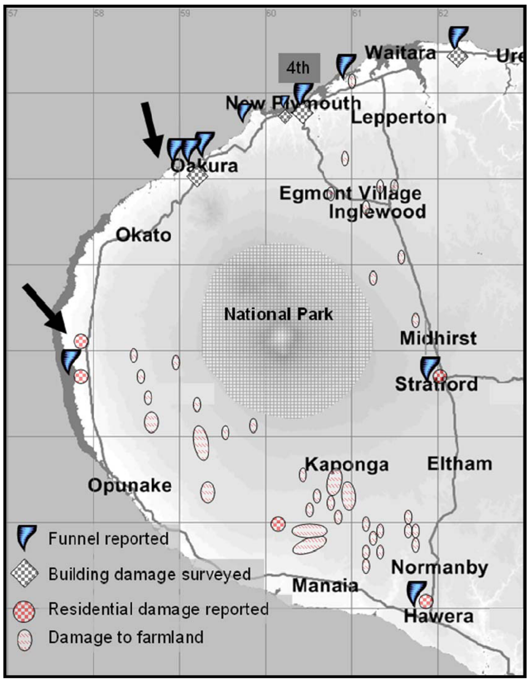

Fig. 2 Location of reported tornadoes and wind-damage in Taranaki for July 5, 2007. The farmland damage was documented from Helicopter by Taranaki regional council staff. Note, parts of the New Plymouth CBD experienced an F0-F1 tornado the previous day (marked by the text "4th")

strikes. Many trees were downed and over 70 houses (mainly in Oakura) badly damaged. The total direct cost of the damage was estimated at NZD $7.0 million.

2.1 Taranaki damage survey

Direct-damage assessments using engineering and scientific experts following wind-storms have been rare in New Zealand. To our knowledge an unpublished survey of the March 10, 2005 Greymouth tornado was the first such study. The Taranaki tornado event provided an opportunity to collect valuable data concerning the nature of the event, estimate wind speeds, assess the housing vulnerability dependent on age, condition, construction materials, and design standards. The data would be used to confirm existing fragility curves built into New Zealand's RiskScape hazard loss modelling tool (Reese and Smart 2008).

The survey was conducted 4-5 days after the event with the major focus being on Oakura. Some clean up and repairs of minor damage had been done in this time, but major damage was still visible, although temporary sheltering using tarpaulins hid important details of damage, although this disadvantage was overcome by talking to property owners. Damage was assessed using a "modified" Boughton (2007) damage assessment template as used for Cyclone 'Larry'.

Some undamaged houses in the vicinity of damaged houses were also surveyed for comparison purposes. A total of 56 damaged houses were surveyed, 2 were in need of demolition, 13 required structural assessment, and 6 were uninhabitable. Data on heavy objects which were moved, e.g., a

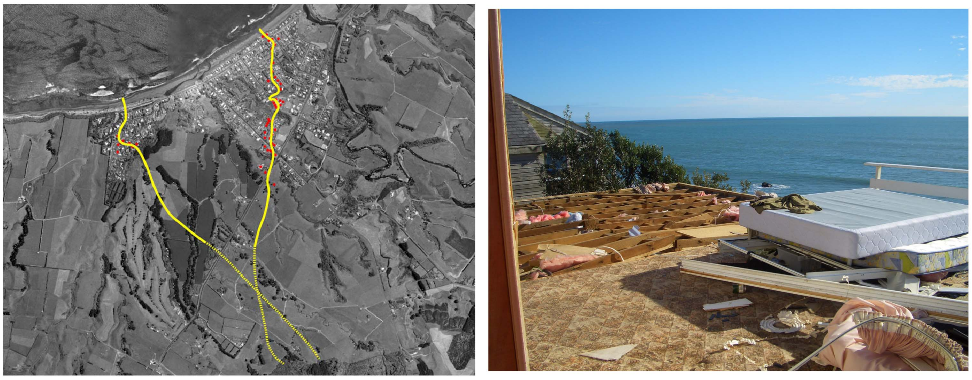

Fig. 3 Assumed paths of the two Oakura tornadoes that caused property damage around 1720 NZST July 5, 2007. The red dots indicate houses that were damaged and surveyed. The distance between the points where each tornado came ashore is 1100 m. The lower panel indicates what remains of the upper level of a sea-shore property after the northern tornado came ashore. (Photo courtesy of P. Scantlebury, Taranaki Regional Council)

2000 kg shipping container, and bent road signs was also gathered to help estimate wind speeds. The paths of the two tornadoes that caused damage in Oakura are shown in Fig. 3(a) and an example of the damage done to houses is clearly illustrated by the photograph in Fig. 3(b). Note, a third and small tornado was also seen in Oakura but did not damage any property. Both paths were about 2.5 km long and the average width of the more destructive tornado (eastward) was 50-60 m, and 20-30 m for the other. The smaller tornado was rated F1 at the locations where it damaged houses, but it possible that speeds may have been in the F2 range as it came ashore and tipped over and flung a caravan in the air at a seaside campground. Note, within this paper, the used of the word "rated" relates to the estimate of peak wind speeds at a specific location along a tornado path and does not refer to any official classification of a tornado.

The more destructive tornado was rated F2-F3 at seven properties, F2 at twelve, F1 at twenty-two, and F0 at six properties. The tornado caused severe damage as it came ashore, then seems to have weakened for a time then re-intensified as it caused near total destruction for a small part of its path and then weakened again as it headed out over farmland to the south of town.

Two clear trends emerged for this event; (i) concrete roof tiles performed well, while sheet-metal and metal tiled roofs were worst affected, and (ii) houses built after 1980 performed better. The newer houses were subject to higher design standards and provided a reasonable level of resistance to tornadoes of this magnitude, even though the loadings code used did not specifically account for tornadoes. In terms of the RiskScape fragility curves the degree of damage (damage ratio) was consistently much less than the indicated by the fragility curve for a given gust speed (Fig. 4). We attribute this to a combination of the short impact duration (only a few seconds) for this event and underestimates of repair costs for "minor" damage.

2.2 NZLAM modelling

From the paths of the two tornadoes we surmised that a thunderstorm with a small-mesocyclone (diameter of a few km) moving rapidly to the SSE was responsible for spawning the Oakura tornadoes. From the satellite image (Fig. 5(a)) the same is likely true of other tornadoes that were

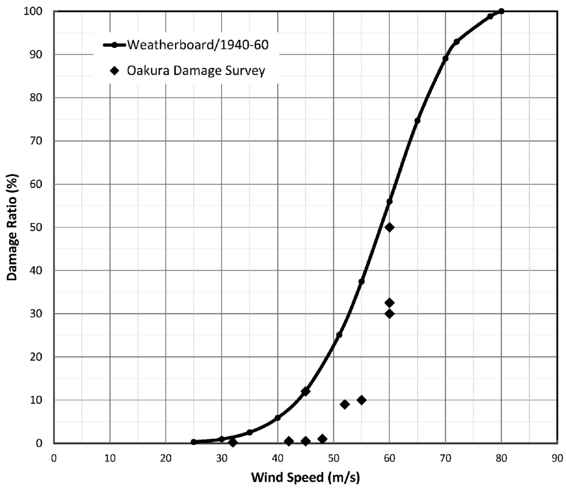

Fig. 4 Percent damage (Damage Ratio) as a function of wind speed (estimated) for Timber framed, weatherboard homes in Oakura following the tornadoes of July 5, 2007

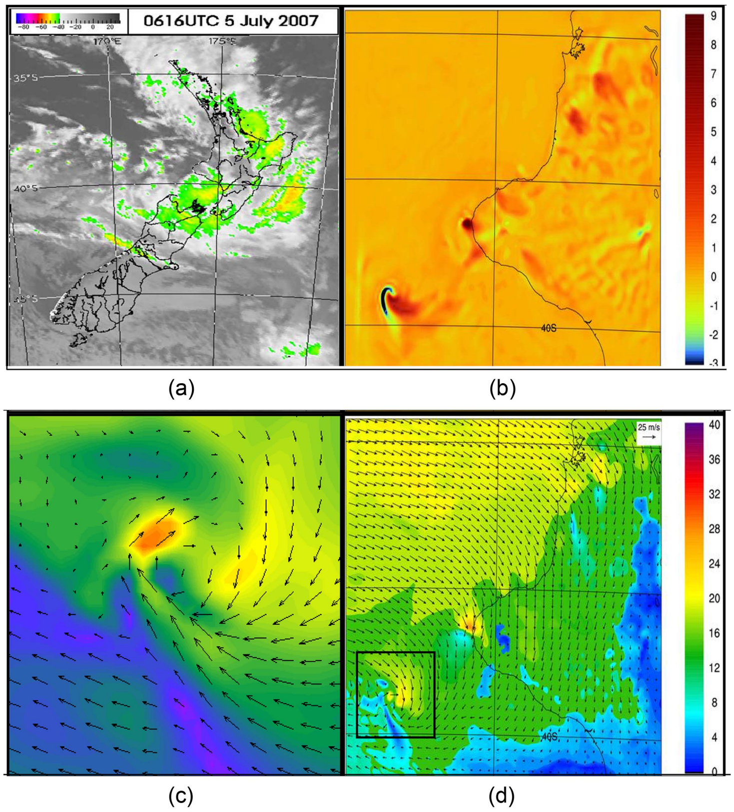

Fig. 5 (a) Satellite (IR) imagery over New Zealand at 1816 NZST July 5, 2007 showing the mesoscale cloud signature centred offshore and south of Taranaki bight. NZLAM-2 km simulated fields (valid at 1830 NZST) of (b) vertical motion (ms^{-1}) at 925 hPa, (c) the storm relative motion (vectors) and wind speed (ms^{-1}) at 850 m agl for the area within the black box shown in (d) the 925 hPa wind speed (ms^{-1}) and direction spawned along the northern Taranaki coasts. However, this satellite image suggests a much large mesocyclone (diameter of ~50-100 km) may have spawned the numerous tornadoes over rural southern Taranaki.

To investigate further this issue, NZLAM, which stands for New Zealand Limited Area Model was used to study the event. NZLAM is actually a specialized version of The MetOffice™ (United Kingdom) model called the UM (Unified Model – see Staniforth, 2004 for a comprehensive description) that has been adapted and configured to produce forecasts and simulations of weather and atmospheric flows over a large region surrounding New Zealand and which is bounded approximately by longitudes 140 °E to 170 °W and latitudes 60 °S to 20 °S. Some of the important model configurations and parameter settings of NZLAM are given in Table 1.

NZLAM was used to re-forecast the weather over Taranaki for July 5 at horizontal resolutions of 12 km, 4 km and 2 km. At 12 km, 3-Dimensional Variational Data Assimilation plus First Guess at Appropriate time (3DVAR+FGAT, see Lorenc and Rawlins (2005) for a detailed explanation of these terms) was used. The 4 km forecasts used no data assimilation (which would be computationally extremely expensive) and were done to produce boundary conditions for the 2 km forecasts. The 2 km forecasts which also had no data assimilation were done with both explicit and parameterized representations of convection in an attempt to understand the processes that contributed to the development of the tornadoes. In this article we briefly summarise the main results obtained while a paper describing in more detail the set of numerical experiments and a more comprehensive dynamical analysis of this event is currently nearing completion.

Table 1 Important parameter settings for NZLAM forecasts described in this report

Parameter	NZLAM 12 km Setting (4 km and 2 km are listed only if different)
Domain size nx,ny,nz	324 × 324 × 38, 200 × 200 × 38 (4 km), 150 × 150 × 38 (2 km)
Time step	300 s, 30 s (4 km), 15 s (2 km)
Radiation time step	3600 s, 900 s (4 km), 900 s (2 km)
No. levels in boundary layer (i.e., altitudes less than approx 1500 m)	13
Radiation scheme	3A (General 2-stream radiation, see Edwards *et al.* 2004)
No. of segments/bands	2/5
Convection scheme	4A (penetrative mass flux scheme, see Maidens *et al.* 2004), 4A (4 km), 4A + none (2 km)
Includes momentum transport	yes
CAPE timescale	1800 s
Defining Anvil and tower factors	3.0 and 0.25
MPARWTR	0.001 kg/kg
Updraught factor for cloud water	0.12
Diffusion scheme	2A (explicit, see Staniforth 2004)
Horizontal diffusion	standard
Vertical Diffusion	off
Diffusion coeffs for wind, theta, and moisture	K = −1.0, N = 0

The 12 km simulations indicated a strong cold pool aloft and the development of a small low pressure system in the Tasman Sea west of central New Zealand, with high values of Convective Available Potential Energy (CAPE) and Storm Relative Helicity (SRH) in the region where the tornadic thunderstorms developed. The 2 km simulations showed the development and rapid southeast movement towards Taranaki of strong convection with updrafts of 7-10 ms^{-1} (Fig. 5(b)). Two significant mesocyclones, marked by the dipole patterns in wind speed and the rapid turning of the wind vectors in Fig. 5(d) are also evident. A well defined rear-flank downdraft has developed with the southernmost mesocyclone, and the classic tornadic thunderstorm (Bluestein 1992) structure is highlighted when the storm relative motion vectors are overlaid on wind-speed (Fig. 5(d)) with the location of likely tornado development northern side of the mesocyclone. These features quickly developed and decayed and were at their most intense phase for less than one hour, consistent with the fact that all the reported tornadoes occurred in a 40 minute period.

The forecast timing of the development of these was very good being around 1800 NZST. Location errors are evident if it is accepted that the southernmost simulated mesocyclone corresponds to the dominant feature evident in satellite imagery. We conclude based on the NZLAM simulations and the satellite imagery that a large mesocyclone developed from a strong convective thunderstorm and that this spawned the outbreak over southwest and southern Taranaki. In terms of uniqueness for New Zealand, it seems the physical dimensions of the mesocyclone were much larger than normal and the simulation of such a well-defined rear-flank downdraft is likely a first for New Zealand meteorology.

3 Greymouth easterly storm of July 30, 2008

On July 30, 2008, a very strong and large mid-latitude storm in the Tasman Sea approached the North Island (see Fig. 6) bringing a deep (winds were still from the south-east winds at 500 hPa with flow reversal around 300 hPa) easterly to south-easterly flow across the upper half of the South Island. Damage due to winds was reported in several areas on the western (and in this case, lee) side of the mountains. The Cobden suburb of Greymouth (Fig. 7) was particularly badly hit with more than one hundred houses suffering damage – mainly to roofs. At Greymouth Airport the official maximum recorded gust of 29 ms^{-1} occurred between 1600 and 1700 NZST, with the mean speeds around this time being 15 ms^{-1}. However, two private weather stations at Cobden recorded maximum gusts of 43 and 47 ms^{-1}. Residents in Cobden noted that the wind came in "huge" gusts and seemed to be "funnelled around the hills" (so would have been coming from the south-east).

3.1 Greymouth damage survey

Understanding the vulnerability of New Zealand homes and the exposure of homeowners, insurers, and government to natural hazards such as severe winds and earthquakes is important to the central government. A damage survey was conducted in Greymouth because the pre-dominant building stock there, being 50 to 100 year old timber/weather board homes with sheet-metal roofs, is common in many other parts of New Zealand. Additionally our experience, which is similar to that for the United States documented in Trapp *et al.* (2006), has been that a damage survey allows estimates of wind speeds to be made at locations where winds are likely to be considerably higher than the nearest official recording site and, gives a better indication of the scale of the event than

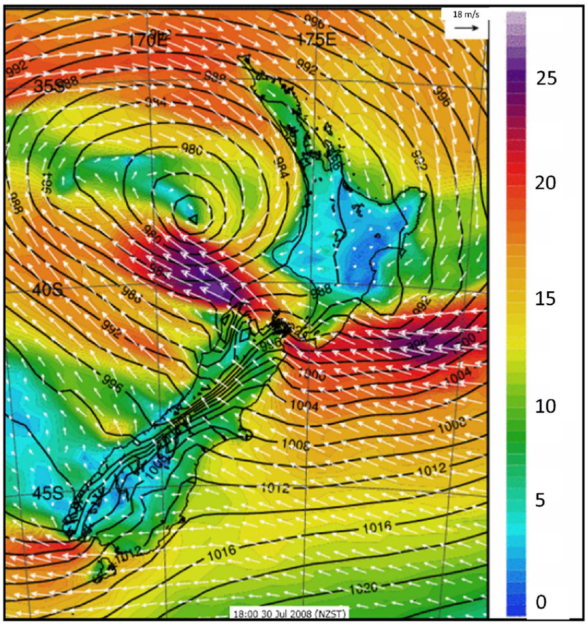

Fig. 6 NZLAM modelled Mean Sea level pressure (2 hPa contour intervals) and surface (10 m agl) winds at 1800 (NZST) July 30, 2008 at forecast hour 12. Note the area shown is only a subset of the entire NZLAM domain

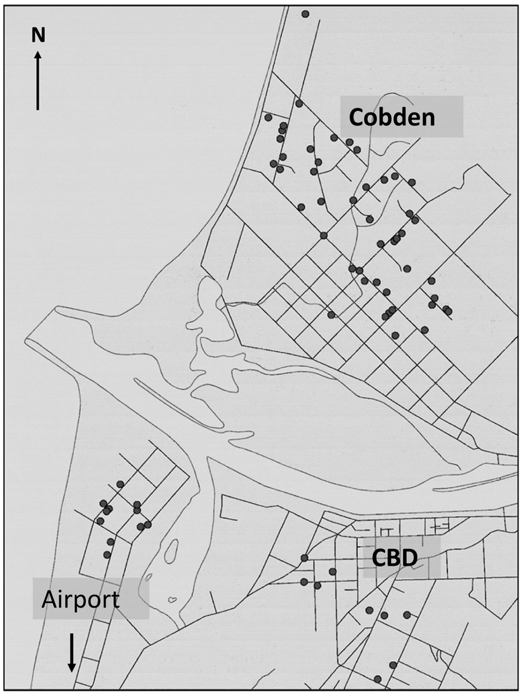

Fig. 7 Map of Greymouth showing Fire Service call-outs (dots) for the CBD and Cobden on July 30, 2008. Note, Greymouth Airport climate station is located about 1 km off the bottom left of the map. The call-out data was supplied courtesy of New Zealand Fire Service

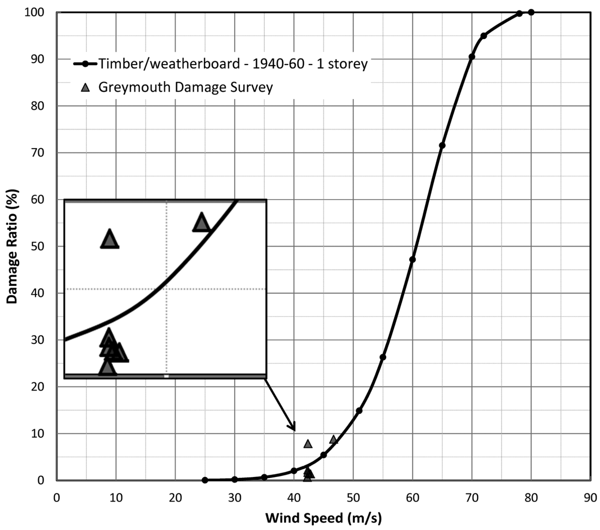

Fig. 8 Percent damage for July 30, 2008 event as a function of wind speed (estimated) for Sheet-metal roofed, Timber framed, weatherboard homes in Cobden, Greymouth

relying on media and official observations.

Fig. 7 shows where the damage occurred in Greymouth and most of these sites were included in our survey. The survey found that greater than 30% of building and roof damage was caused by debris and the damaging winds likely were in the range of 40 to 45 ms^{-1}. From the pattern of the debris damage to walls in Cobden, the direction of the severe winds was concluded to be from the SE and in line with where the Grey River cuts through the range of coastal hills (about 1 km away and with approximately 300 m high hills either side). The Weibull-shape fragility curve, already used within the New Zealand risk assessment tool (RiskScape) was confirmed for the data gained here, albeit over a more limited range of wind-speeds than for the Taranaki survey, see Fig. 8. However, the damage in some cases (as was the case for the Oakura tornadoes) was less than indicated by this fragility curve especially for lower gust speeds near 43 ms^{-1}.

Given the direction and speed profile of the flow crossing the Southern Alps, a down-slope windstorm (Durran 1990) was suspected as being responsible for the gusts. Here there was a reversal of wind with height at 300 hPa well above mountain top level and conditions for trapping and amplification of gravity waves existed – so wave breaking leading to a down-slope windstorm was likely. However, the small coastal range of hills to the east of Greymouth might have been expected to shelter the town (about 40 km downstream of the main range) from the severe winds except perhaps where the Grey river cuts through the hills. Here, at the most exposed site (around the bridge), where channelling effects would be strongest, there is little vulnerable housing or infrastructure to damage. Local downslope winds off the 300 m high hills immediately to the east of Greymouth also seem unlikely given the direction of these slopes compared to resident's accounts of wind direction.

The GERRIS (Popinet (2003)) computational fluid dynamics model (maintained at NIWA) was used to try and better understand the possible causes of the damaging winds in Cobden by imposing the larger scale tropospheric flow on July 30 over an idealized 3-D terrain representing the Southern Alps and Greymouth region. Upstream wind and potential temperature profiles from the NZLAM

12 km forecast archives valid for 1700 NZST July 30 2003 (see section 2) were used to provide initial conditions to GERRIS.

3.2 Brief GERRIS model description and results

GERRIS is a finite volume, Large Eddy Simulation (LES) model with an adaptive mesh and automatic refinement of the grid, i.e., as a simulation proceeds resolution is increased in regions where turbulence or strong gradients of temperature or momentum develop. It solves the time-dependent incompressible variable-density Euler, Stokes or Navier-Stokes equations It is second order in space and time and solves the linear and non-linear shallow-water equations. By "shallow water" it is meant that horizontal length scales are assumed to be much greater than the vertical depth scales. Key settings of GERRIS for the simulations conducted here are given in Table 2.

Two 3-D simulations were conducted, one with friction and one without friction. Vertical cross-sections along the flow for these simulations are shown in Fig. 9. The simulation without friction (Fig. 9(a)) reproduced a hydraulic jump feature which developed over the steep lee-slope and propagated through the domain (suggesting a critical Froude number of ~1). Highly turbulent flow features and near-surface speeds up to about 40 ms^{-1} representing a speed-up by a factor of 3 are evident. The simulation with friction included (which is computationally much more expensive as it requires much higher resolution to represent the turbulence) changed the solution dramatically, with the high wind speeds being confined much closer to the lee-slope, however large-amplitude mountain waves, wave breaking and rotors, capable of producing strong surface gusts were simulated (Fig. 9(b)).

The simulation without friction and for which the hydraulic jump propagated to the coastal range developed a turbulent plume of high speed air (enhanced by 10-15%) through the gap in the idealized coastal hills (Fig. 10). This plume was not steady nor oriented directly downwind of the gap, but wandered at different times between being southwest of through west to being northwest of the gap. This is interesting and may explain the presence of damage south of the Grey river (Fig. 7)

Table 2 Key settings for the idealized GERRIS simulations of the gap flow

Parameter	GERRIS settings/comment
Domain size nx,ny,nz	Variable resolution (10-300 m)
Grid	Adaptive, Finite volume formulation
Time step	~ 1 s
No. levels in boundary layer	13
Radiation scheme	None
Moist Physics	None
Turbulence closure	None/(LES)
Convection scheme	None
Horizontal/Vertical diffusion	Off
Initial profiles	From NZLAM-12 km forecasts, Strong easterly below 500 hPa, Zero flow around 300 hPa
Terrain	Idealized 3-D – Southern Alps plus coastal range with gap.

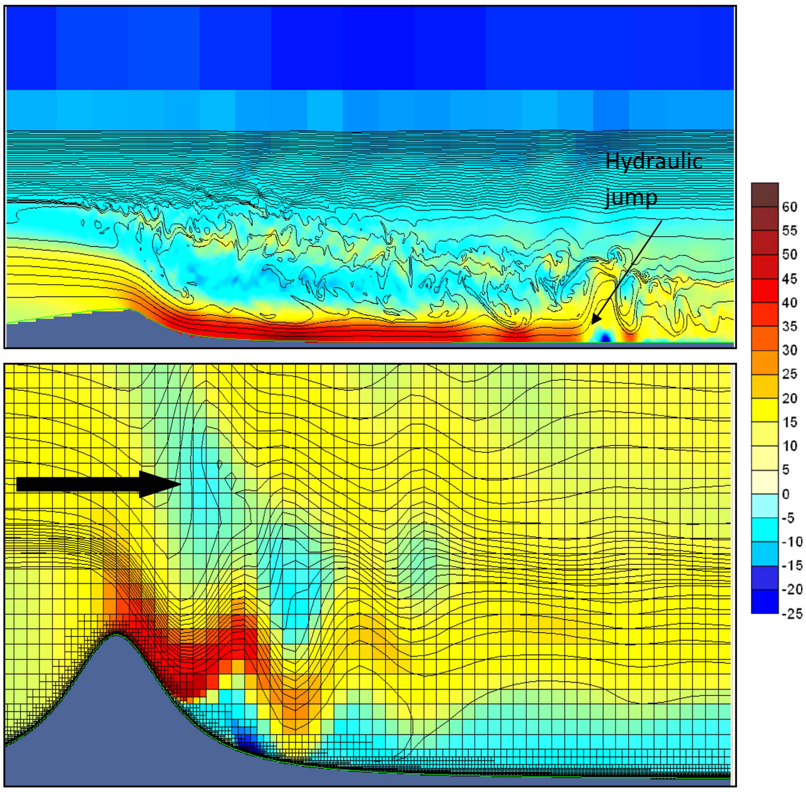

Fig. 9 Wind speed (colour shaded (ms^{-1})) and isentropes (3 K) for an idealized cross-section of the Southern Alps as simulated by GERRIS without (a) and with (b) the effects of surface friction included. The black arrow indicates the easterly flow that dominated at levels below 400 hPa on July 30, 2008. The black squares of variable size indicate the adaptive grid

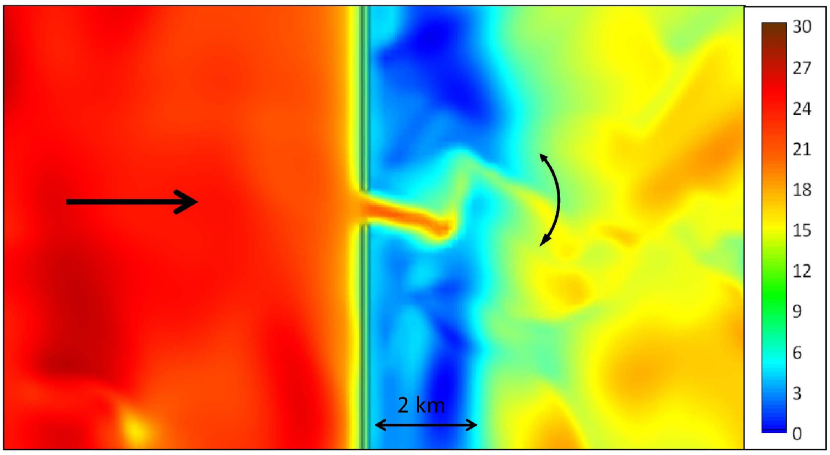

Fig. 10 A top down view of near surface wind speeds (ms^{-1}) from an idealized GERRIS simulation of strong lee-slope winds (thick black arrow) impacting upon a downwind range of hills with a gap. The smaller black arrow indicates the range in which the thin filament of stronger winds channelled through the gap meandered during the course of the simulation

in addition to the Cobden damage and the lower wind speeds at Greymouth Airport as well the residents reports of the "gustiness" of the event–which can be interpreted as indicating extended periods with low wind gusts.

4 Conclusions

Northwesterly down-slope storms that impact Canterbury are much more frequent than downslope easterly storms impacting the West Coast because strong zonal (i.e., westerly) flows over New Zealand are much more common than strong easterly flows. In Fig. 11, the maximum daily wind gusts during north-westerlies at various Canterbury stations (several different periods) have been plotted against the maximum Hokitika-Christchurch pressure difference for that day. (The fact that there are so many cases should convince the reader that westerlies predominate!). It is interesting to note that pressure gradient of the easterly case (multiplied by −1 for plotting purposes) is one of the higher magnitudes since 1975. Further, the wind speeds only seem notable since property damage occurred, a damage survey ensued and efforts made to obtain speed estimates based on (i) damage characteristics, (ii) private records , and (iii) computational flow models. If the event had occurred over a rural area, damage would have been likely confined to a few trees and a hay-barn, no survey would have been done and the Black Cross in Fig. 11 would be absent and the much lower Greymouth Airport value (29 ms^{-1}) would be the "noteworthy" maximum gust for the event. The same kind of sampling problem also likely exists on the Canterbury side of the Southern Alps. Consider, October 4, 2008 a strong gusty north-westerly was reported over the region with the cross-winds disrupting flights at Christchurch airport. The maximum record gust at any leeward sites was 30 ms^{-1} at Winchester. However, on this day a Centre-Pivot irrigator was blown over and destroyed near Methven. These heavy and expensive pieces of equipment are designed to withstand speeds of 40 m/s^{-1}. So with similar (to the Greymouth easterly event) magnitude pressure gradients, similar low-land official maximum gusts were recorded yet much higher gusts caused property loss.

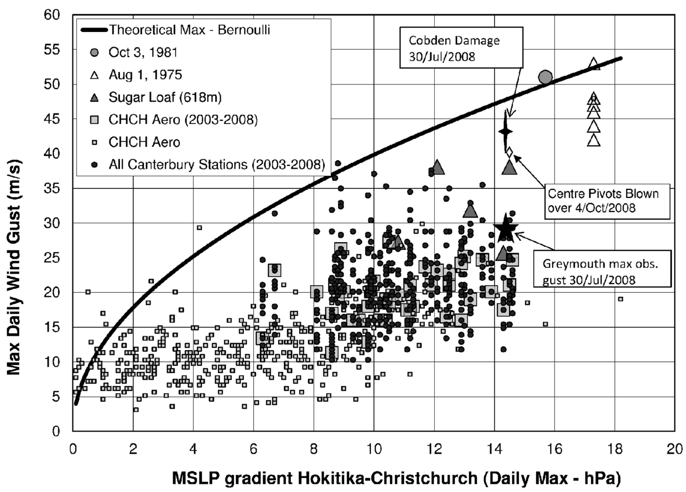

Fig. 11 Daily maximum pressure gradient across the Southern Alps (Hokitika-Christchurch) versus maximum daily wind gusts for various Canterbury weather stations. The curve representing the theoretical Bernoulli maximum is shown

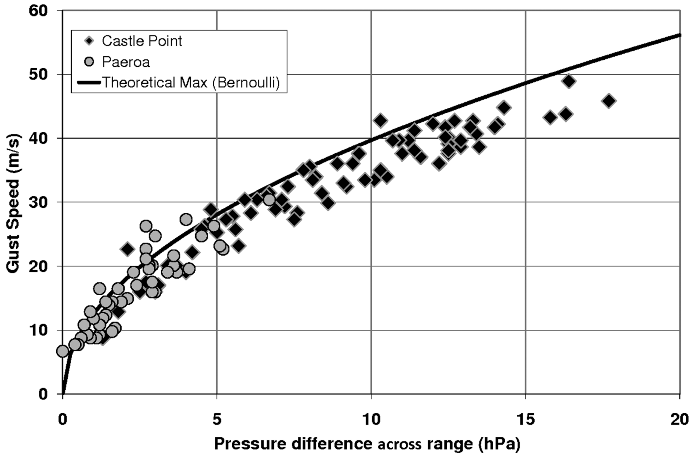

Fig. 12 Pressure gradients across two North Island ranges; the Tararuas (Palmerston North-Castle Point) and the Kaimais (Taurang-Paeroa)) versus maximum gust speeds reported at Castle Point and Paeroa

Anecdotally, (personal communications from insurance industry contacts) damage to centre-pivot irrigators occurs quite frequently (a few instances in the past few years) while no 40 ms^{-1} (or higher) gusts have been recorded at any Canterbury low-land stations.

The other aspect to Fig. 11 which suggests a sampling problem, with respect to extreme gust climatology in Canterbury, is that relating to the "theoretical maximum of Bernoulli". The Bernoulli relationship states that for any particular pressure gradient (Δp) and air density (ρ) the maximum expected wind speed (v) is given by

$$v = (2 * \Delta p / \rho)^{0.5}$$

Observations for other New Zealand ranges show that this relationship holds well (Fig. 12), yet the plot for the Canterbury region (Fig. 11) is ambiguous at best, however the relationship seems more plausible when more extreme events occur and when damage has occurred so that estimates from damages of gust speeds can be included.

Sampling is also an issue that is highlighted when reflecting on detection of mesocyclones such as was responsible for the Taranaki tornado event. It is completely unknown as to how often such large mesocyclone features may develop offshore of Taranaki and other west coast locations where tornadoes are relatively frequently reported in New Zealand. A radar capable of detecting such a feature was not installed at New Plymouth Airport until 2008. Important petroleum industry infrastructure is located offshore of Taranaki, so future research should be aimed at analyzing radar data from New Plymouth for mesocyclone signatures and also a long-term, historic high-resolution numerical weather reanalysis for the whole of New Zealand needs be done to assess this risk.

The results obtained from the two case studies presented here demonstrate that damage surveys and high-resolution modelling of winds during severe events are an important part of current research and have the potential to be important tools for New Zealand in interpreting long-term gust records and in the understanding the spatial patterns of risk from extreme winds.

Acknowledgments

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