A severe frontal rain event over the lower North Island of New Zealand with intense embedded convective banding

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Abstract

On Thursday May 14, 2015, an active front passed over the greater Wellington region of New Zealand with embedded bands of intense convection and very high rain rates. The front had a northwest to southeast orientation and the winds were predominantly from the northwest so the front moved along its length meaning the intense rainfall associated with the embedded organised bands was able to remain in place for up to half an hour or so. This led to severe localised flooding with return periods of just over 100 years in many areas from Waikanae southwards. Local models accurately forecast aspects of this event, for example rain, totals of up to 40 mm in an hour, but generally failed to get both the locations and timings of the most intense rain correct. In general, the forecast rain totals improved with model resolution but there was considerable variation depending on initial analysis time and the latest forecasts were not always the best. In this paper we investigate the key features that contributed to the intense rain and whether they can be simulated with current operational weather models. We also note the existence of a low level moist absolutely unstable layer in the lowest 2 km arising from advection of very high specific humidity air from the subtropics through the width of the front.

1. Introduction

On Thursday May 14, 2015, an active front passed over the greater Wellington region of New Zealand causing severe flash flooding on both sides of the main dividing range of the lower North Island, effectively cutting Wellington off from the rest of the country. Flooding is quite common in New Zealand and it is in fact the most frequently occurring and costly weather-related hazard. Insurance claims for different weather-related hazards (i.e. excluding earthquakes) from the Insurance Council of New Zealand website (https://www.icnz.org.nz/natural-disasters/cost-of-natural-disasters/), indicate that between 1968 and 2018 almost 75% of the total claimed costs are due to flooding.

Flooding can often be associated with prolonged rain in the main dividing ranges of both main islands and subsequent overtopping of the banks of the main rivers as they flow down to the sea or intense convection and very high local rain rates operating for much shorter duration. The May 2015 case was of the latter type and associated with embedded bands of intense convection and very high local rain rates with totals of over 40 mm

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in an hour in some places. Rather than the main rivers causing the flooding, it was local creeks becoming raging torrents that caused the most severe surface flooding. Usually, convective elements in a front would only remain over a fixed site for several minutes but this front had a northwest to southeast orientation and the winds were predominantly from the northwest, so the front moved along its own length meaning the intense rainfall associated with some of the organised bands was able to remain in place for up to half an hour. This led to severe localised flooding with return periods of just over 100 years for 24-hour rain totals (based on data from the High Intensity Rainfall Design System (Carey-Smith et al., 2018)) in many areas of the lower North Island from Waikanae southwards. For this case, we are interested in why the convective elements of this particular event had a predominantly banded structure, whether they are resolved by locally available Numerical Weather Prediction (NWP) models and how sensitive their locations are to forecast initial conditions.

The seminal New Zealand thunderstorm climatology was published by C. G. Revell (1984). This study found that orographic and surface heating influences dominated thunderstorm activity, though most thunderstorms were also associated with frontal or surface wind convergence. Eastern areas and the central North Island showed a distinct diurnal and annual pattern in thunderstorm activity, attributed to the influence of surface heating. Elsewhere, higher thunderstorm frequencies were noticed during winter, speculating that this was a result of orographic influences (C. G. Revell, 1984; Sturman & Tapper, 2006). There have been very few studies of convection over New Zealand undertaken since then as pointed out in Hawke (2017). Most of these are works by New Zealand MetService staff and are not published externally. One of the difficulties associated with studying convection in New Zealand is lack of observations. The New Zealand radar network is one source that provides reasonable coverage and we are grateful to the New Zealand MetService for access to the 7.5-minute radar imagery for this storm. There is also a 12-hourly radiosonde flight from nearby Paraparaumu Aerodrome and a relatively sparse network of rain gauges in the greater Wellington region.

In this paper we first look at rainfall observations in the region and compare them with rainfall estimates that were available at the time from three NWP models available at NIWA: the UK Met Office run global Unified Model (UM) N768L70 - approximately 17 km grid resolution in our region; the New Zealand Limited Area Model (NZLAM) - 12 km grid; and the New Zealand Convective-Scale Model (NZCSM) - 1.5 km grid. To evaluate the effect of increased resolution we also ran a very high resolution one-way nested case-study configuration of the Unified Model with horizontal resolutions of 1.5 km, 300 m and 100 m nested in the UK Met Office Global model. Neither NZCSM nor any of the three nested configurations used parameterised convection.

All of these models are local configurations of the UK Met Office Unified Model (Brown et al., 2012), which uses a semi-implicit, semi-Lagrangian dynamical core formulation known as ENDGame (Wood et al., 2014). The UM and the very high-resolution one-way nesting strategy used in this study has been applied previously in studies of convective processes (for example Hanley et al. (2014) and Lean et al. (2019)) and the burgeoning role of high-resolution convection-permitting models has been discussed in Clark et al. (2016). The majority of these UM-based studies have to date focussed on cases in the UK. NIWA has been using the UM for its NWP forecasts at meso-scale resolutions since 2007 and introduced the 1.5 km resolution NZCSM in late 2014. Since an early attempt to simulate a severe weather event over the Southern Alps at high-resolution (then deemed to be 1km horizonal resolution, Webster et al. (2008)), recent New Zealand-based case studies using this experimental strategy with the UM have focussed on wind (for

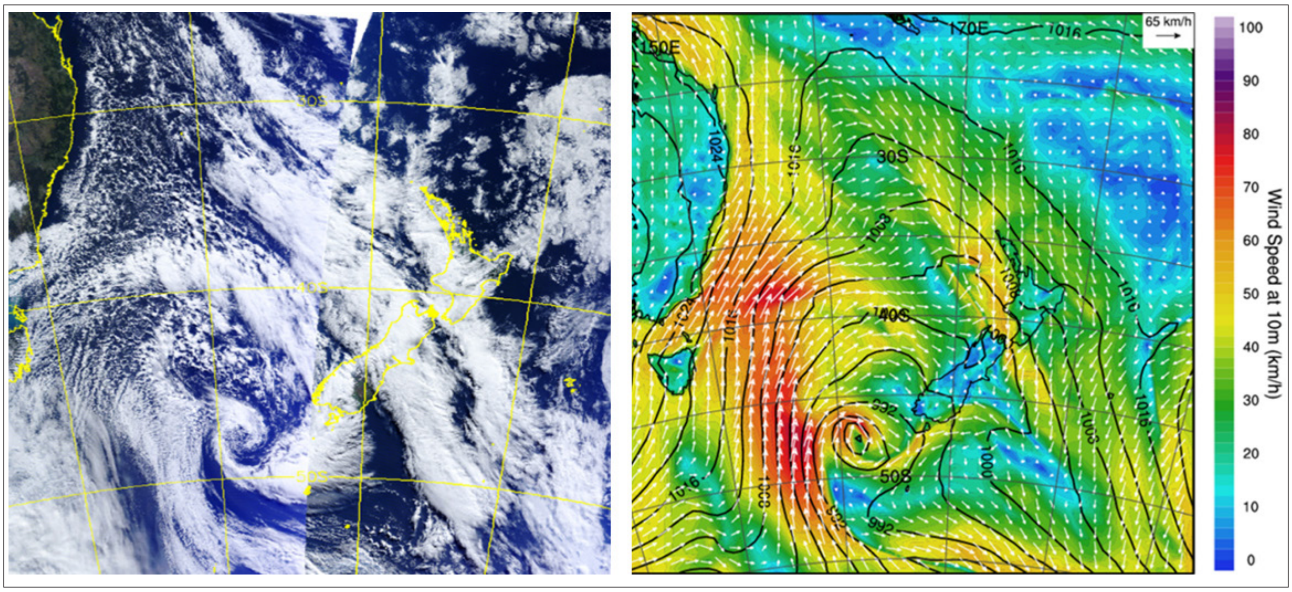

Figure 1: Left: MODIS visible image: 1007 to 1145 NZST, 14 May 2015. Right: NZLAM forecast MSLP and wind for 1100 NZST from the 0600 NZST analysis also on 14 May 2015.

example Yang et al., (2016)) and coupling the NZCSM to downstream hazard tools such as a hydrological model for local flood forecasting (Cattoen et al., 2016). Thus, this study is a return to focussing on high resolution modelling of precipitation in the New Zealand context.

Results from the nested model allow us to assess the sensitivity of model rain forecasts to model horizontal resolution. We then look at the sensitivity of model rain forecasts to initial conditions by comparing the forecasts started at four successive analysis times, six hours apart. Finally, we look more closely at the structure of the key features that led to the intense rain and investigate whether they can be well simulated with current operational weather models.

To illustrate the synoptic scale setup, in Figure 1 we show the infrared satellite image for 1007 to 1145 hrs NZST and the NZLAM forecast sea level pressure and wind for 1100 hrs based on the 0600 hrs analysis both on 14 May 2015 NZST. Note the subtropical origin of air ahead of the easternmost cloud band over New Zealand and its northwest to southeast orientation.

2. Comparison of Rainfall Observations with Model Predictions

2.1 Radar comparisons

In Figure 2 the locations and names of rain gauges that will be referred to in the following discussion and their corresponding observed maximum hourly rainfall in mm during the period 2100 hrs Wednesday 13 to 2100 hrs Thursday 14 May, 2015, are presented. Figure 2 also shows the maximum hourly rainfall in mm at each NZCSM model point for the same period. Maximum observed hourly totals at the observing points ranged between 8 - 40 mm. The NZCSM model predictions show a similar range of hourly totals, but not always in the same places as the observations. One interpretation of this might be that the model is capable of resolving the structures that produce rainfall of this intensity, but where the bands actually form is very dependent on initial conditions. To examine this idea further, Figure 3 presents instantaneous surface rainfall rates as predicted by NZCSM for 0800 hrs on Thursday 14 May, for comparison with radar images of estimated surface rain

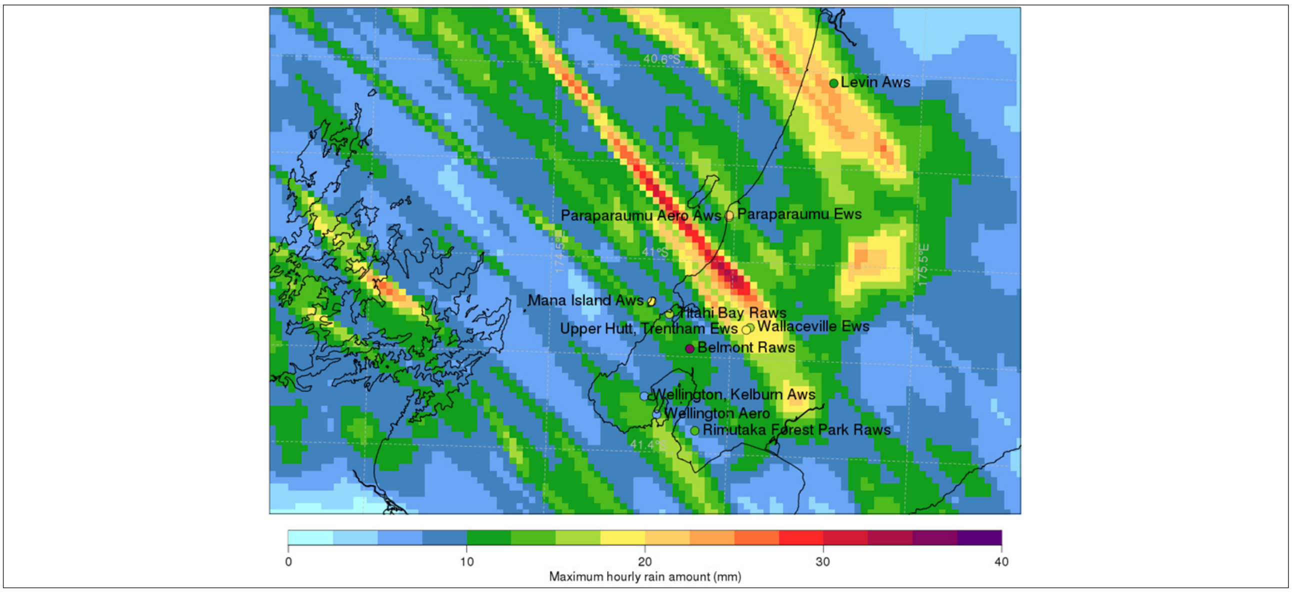

Figure 2: Maximum hourly rainfall at each NZCSM model point during the period 9 pm Wednesday 13 to 9 pm Thursday 14 May 2015 with matching gauge amounts in mm.

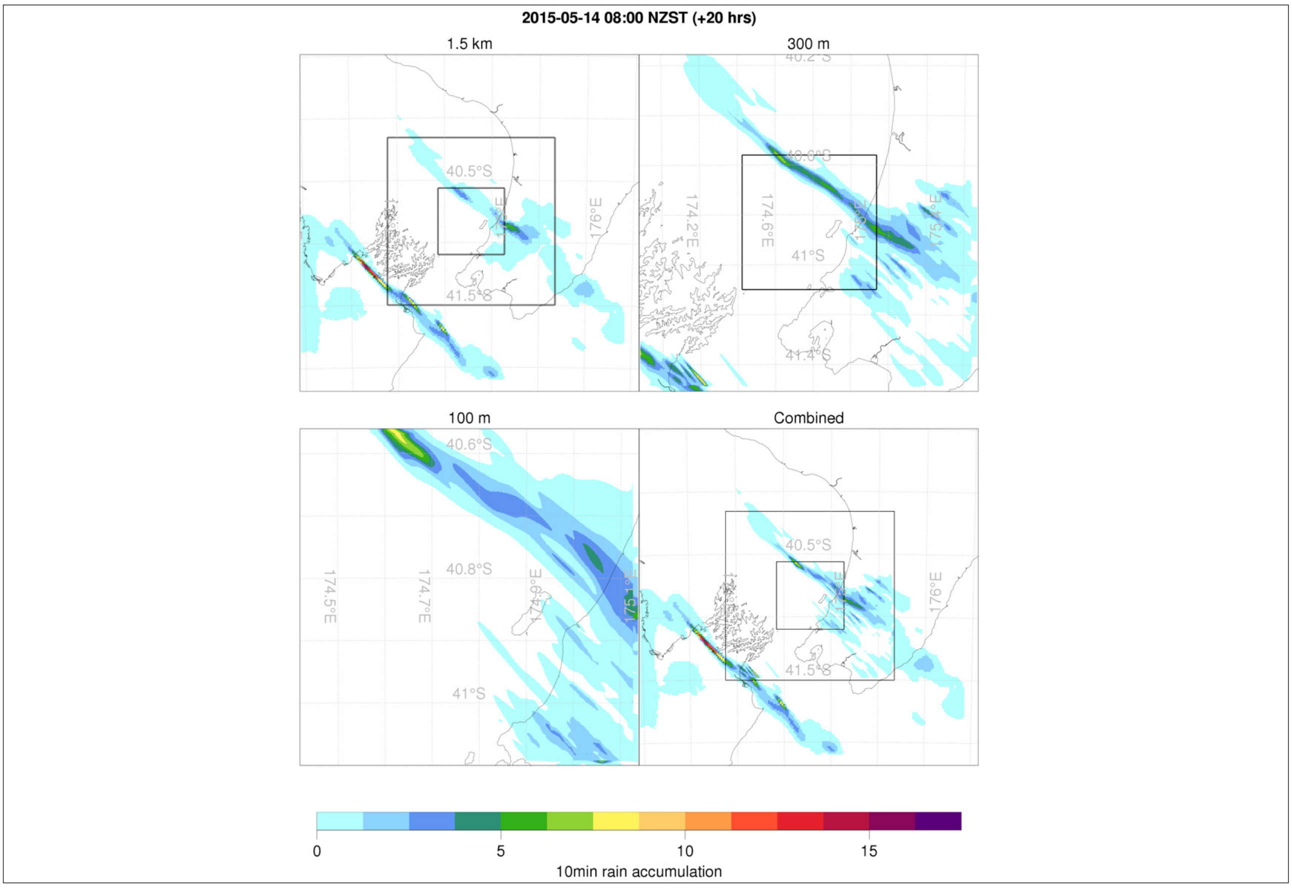

Figure 3: Ten-minute rainfall accumulations ending at 8.00 am, on Thursday 14 May 2015, from the three nested high-resolution models, showing their banded structure. The lower right panel combines all three resolutions into a single image.

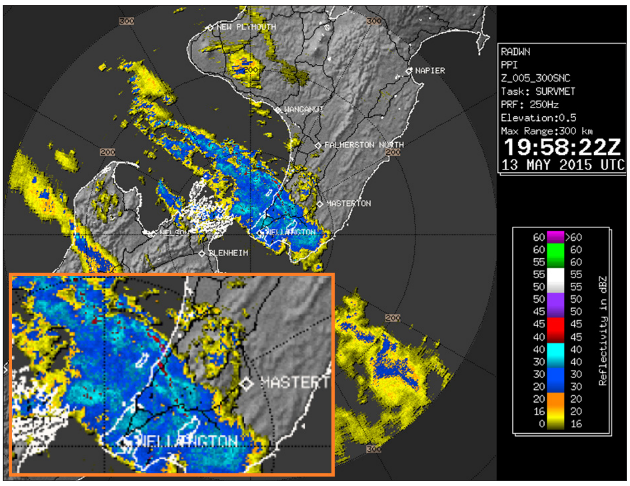

Figure 4: MetService Radar image for 7:58 am Thursday 14 May 2015 showing a band of frontal rain (blue) with embedded organised bands of intense convection (red). Inset shows enlargement over the Kapiti area.

rate. Two features immediately stand out, 1) the rain has a strongly banded structure, aligned along the direction of the wind (which is predominantly from the northwest) and 2) the intense rain begins out at sea, so this rain is not predominantly orographically driven but is associated with convective structures that are of the order of a km or so wide and several 10s of km long. This can also be seen in the MetService radar image in Figure 4 and in the inset enlargement which shows a band of frontal rain in blue (1 - 5 mm/hr) with embedded organised bands of intense convection 1 - 2 km wide and 10 - 20 km long in red (up to 45 mm/hr) near Waikanae and Paraparaumu for the nearest matching time of 0758 hrs NZST on Thursday May 14. The rain bands forecast by NZCSM are not in quite the same locations nor have the same scale as those depicted in the radar imagery, but they are of similar intensity and orientation and, by inspection of the radar data every 7.5 minutes, moving at similar speeds. As the model resolution increases, the scales of the observed and modelled structures show better agreement.

2.2 *Individual Raingauge Comparisons*

In Figure 5 we show the hourly rainfalls between 2100 hrs Wednesday 13 to 2100 hrs Thursday 14 at six of the rain gauge sites marked in Figure 2. Note all the sites except Wellington Airport have a period with rain totals greater than 15 mm/hr, with Belmont Raws approaching 40 mm/hr at midday. Note the peak rate is reached at the same time at Mana Island and Belmont Raws. The line between these two stations is parallel to the movement of the convective bands and inspection of radar images spaced 7.5 minutes apart indicates a band passing over the two stations between 1100 hrs and 1200 hrs. In fact, the radar imagery reveals that each of the stations has convective

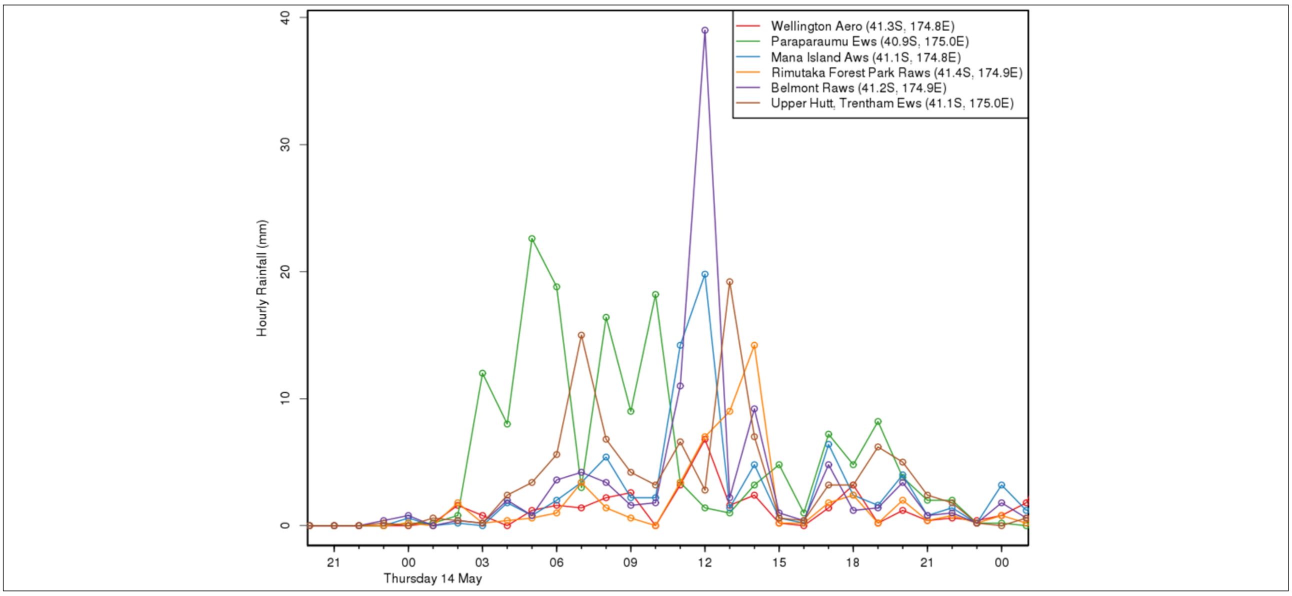

Figure 5: Observed hourly rainfalls at 6 of the sites marked in Figure 2

[1] See http://www.metsoc.org.nz/files/newsletters/2014/poster_careysmithposter_lowres_probprecip.pdf for details

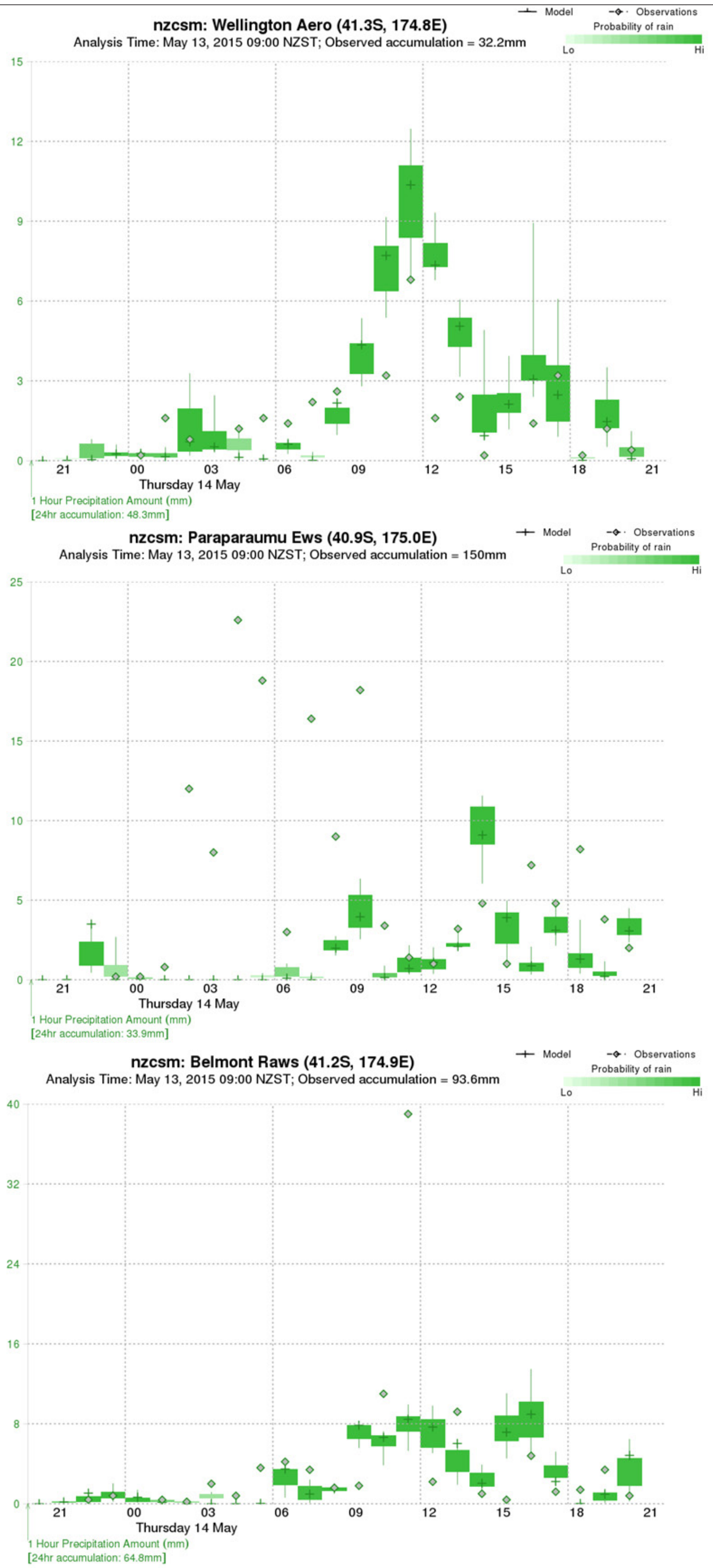

Figure 6: NZCSM predicted and corresponding observed hourly rainfalls at Wellington Aero (top), Paraparaumu EWS (middle) and Belmont Raws (bottom).

bands passing over them during the hour corresponding to rainfall peaks.

Figure 7: View from Petone overbridge looking north over state highway 2 about 12.30 pm on May 14, 2015. Photo: DAVID MORRISON.

In Figure 6 we show meteograms for 3 of the stations in Figure 5 comparing hourly rainfall predictions by NZCSM with those observed. The boxplots show the range of precipitation amounts forecast by NZCSM within a 6 km radius of the location, while the shading corresponds to the proportion of this area having non-zero rainfall. In general, we find that NZCSM does fairly well when the rain totals are below 10 mm in an hour, but fails to get the rain totals (and possibly locations too) correct when they are above 10 mm in an hour. The model fails to predict the periods of intense rain at Paraparaumu between 0300 hrs and 0900 hrs on 14th May. At Wellington, which missed the most intense rainbands associated with the event, the model slightly over predicts the rain totals. The model does quite well generally at the Belmont site but fails to get the isolated 38 mm/hr rainburst at midday and similarly at Mana Island, Upper Hutt and Rimutaka Forest Park (not shown). This value at Belmont stands out dramatically compared to all the other hourly totals at Belmont. However, radar imagery indicates the passage of an intense convective band at that time which would explain the observed rapid flooding of the

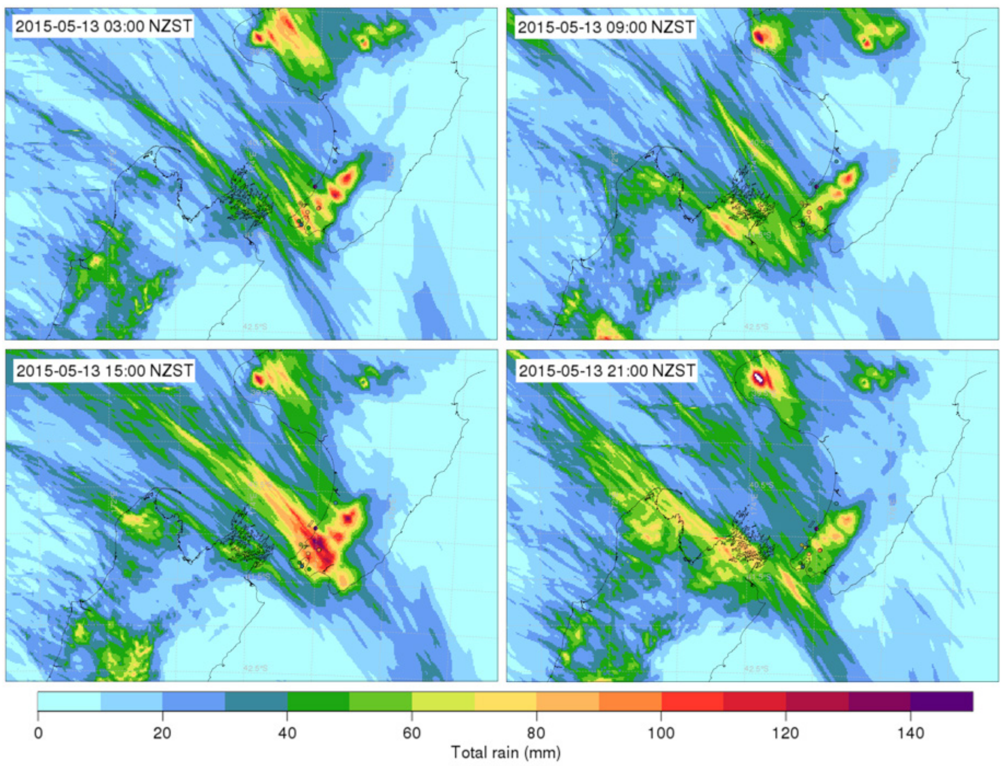

Figure 8: NZCSM predicted total rainfall between 9 pm Wednesday 13 and 9 pm Thursday 14 May, 2015 for four forecast runs initiated at 3 am, 9 am, 3 pm and 9 pm NZST on Wednesday 13 May.

Korokoro Stream, which is fed from the Belmont region, and subsequently State Highway 2 (shown in Figure 7), effectively cutting Wellington off from the Hutt Valley.

2.3 Sensitivity to initial conditions

In Figure 8 we look at the 24-hour rainfall totals for the Wellington Region between 2100 hrs Wednesday 13 to 2100 hrs Thursday 14 May predicted by NZCSM starting from four different initial times: 0300, 0900, 1500 and 2100 hrs NZST on Wednesday 13 May. Matching totals are displayed at the rain gauge sites along with the observations in Table 1. Clearly the 24 hr rainfall totals are sensitive to the initial conditions with the 0300hrs and 1500 hrs runs giving significantly higher totals than the 0900 hrs and 2100 hrs forecasts. In general, the 24-hour totals are reasonably well predicted at the gauge sites, with the exception of Paraparaumu. This considerable variation in model evolution from one run to the next highlights the influence of each model's initial conditions and the stochastic nature of the triggering of convection at fine scales.

2.4 Sensitivity to model resolution

Table 2 shows the effect of model resolution and convective parameterisation on rainfall forecasts for five of the gauge locations shown in Figure 2. For NZCSM, a 1.5 km resolution model without convective parameterisation, median, 95% and 5% percetiles refer to the precipitation amounts forecast by NZCSM within a 6 km radius of the specified location. NZLAM is the regional 12 km resolution model and GLOBAL is the global 17 km resolution model both with convective parameterisation turned on. All the models under-predict the rain at Paraparaumu and generally over-predict the amount at Wellington. At the other three stations NZCSM is best, followed by the Global model and then NZLAM. It is difficult to make categorical statements from such a limited sample but generally the higher resolution NZCSM model gives the best results, although all models miss the intense 6-hour period of rain during the morning at Paraparaumu. Coupled to the sensitivity to forecast initial conditions highlighted in the previous section, it is clear that model resolution plays a role in the ability to correctly simulate rainfall totals on this scale and that a horizontal resolution of 1.5km may still not be

Table 1: 24-hour rain accumulations in mm from 9pm on May 13 to 9pm on May 14 at the gauge sites for the four analysis times and corresponding observations.

	2015-05-13 03:00 NZST	2015-05-13 09:00 NZST	2015-05-13 15:00 NZST	2015-05-13 21:00 NZST	Observations
Levin Aws	23.5	17.5	48.0	31.0	40.4
Wellington Aero	88.4	50.0	66.6	58.2	32.2
Paraparaumu Aero Aws	41.0	35.6	76.9	41.5	142.0
Paraparaumu Ews	40.1	35.3	76.8	40.5	150.0
Wallaceville Ews	77.2	63.7	113.2	63.7	97.8
Wellington, Kelburn Aws	92.4	50.7	61.3	55.5	43.4
Mana Island Aws	78.3	54.2	81.8	36.1	74.8
Rimutaka Forest Park Raws	61.2	46.6	62.2	52.5	50.4
Belmont Raws	78.3	71.7	97.9	58.8	93.6
Titahi Bay Raws	74.2	60.4	80.7	40.0	73.0
Upper Hutt, Trentham Raws	71.7	62.9	116.4	62.5	98.6

Table 2: 24-hour rain accumulations in mm from 9pm on May 13 to 9pm on May 14 at the gauge sites for the various models and corresponding observations.

	NZCSM median	NZCSM 95%	NZCSM 5%	NZLAM	Global	Observations
Wellington Aero	66.0	121.9	25.7	31.4	40.7	32.2
Titahi Bay Raws	84.8	159.9	42.3	60.1	102.2	73.0
Belmont Raws	89.6	159.5	44.6	47.6	75.6	93.6
Wallaceville Ews	114.2	230.8	47.5	34.9	65.0	97.8
Paraparaumu Aero Aws	69.1	178.9	27.6	54.7	87.5	142.0

Table 3: 24-hour rain accumulations in mm from 9pm on May 13 to 9pm on May 14 at the gauge sites for NZCSM, the high resolution nested models and corresponding observations. The NZCSM results are a repeat of those in the third column of Table 1

	NCZSM 2015-05-13 15:00 NZST	Nested 1.5km	Nested 300m	Nested 100m	Observations
Levin Aws	48.0	22.2	22.1		40.4
Wellington Aero	66.6	60.3	59.8		32.2
Paraparaumu Aero Aws	76.9	12.5	25.3	36.2	142.0
Paraparaumu Ews	76.8	12.8	27.0	36.1	150.0
Wallaceville Ews	113.2	58.0	86.4		97.8
Wellington, Kelburn Aws	61.3	63.1	58.9		43.4
Mana Island Aws	81.8	53.3	71.2	88.4	74.8
Rimutaka Forest Park Raws	62.2	60.0	60.4		50.4
Belmont Raws	97.9	56.6	90.6		93.6
Titahi Bay Raws	80.7	54.1	74.0		73.0

enough to properly (or explicitly) capture the convective processes involved.

Table 3 compares 24-hour rainfall totals from the higher resolution nested model runs against observations. The 1.5 km nested model is the same resolution as NZCSM but driven from the UK Met Office global model initial conditions rather than the locally run 12 km data assimilating model (NZLAM). The NZCSM rainfall forecasts show the benefit of local data assimilation, as at many locations the nested 1.5 km model underestimates the 24-hour rain totals by a larger amount than NZCSM. However, as the resolution is increased in the nested model, the rain amounts become closer to the observations. All versions of the model clearly miss the significant rain bands that passed over Paraparaumu in the early hours of May 14th.

3. Structure of the moist layer

In this section we look in more detail at the properties of the moist layer in which the bands of convection develop.

3.1 Horizontal section

In Figure 9 we show a horizontal slice of the wet bulb

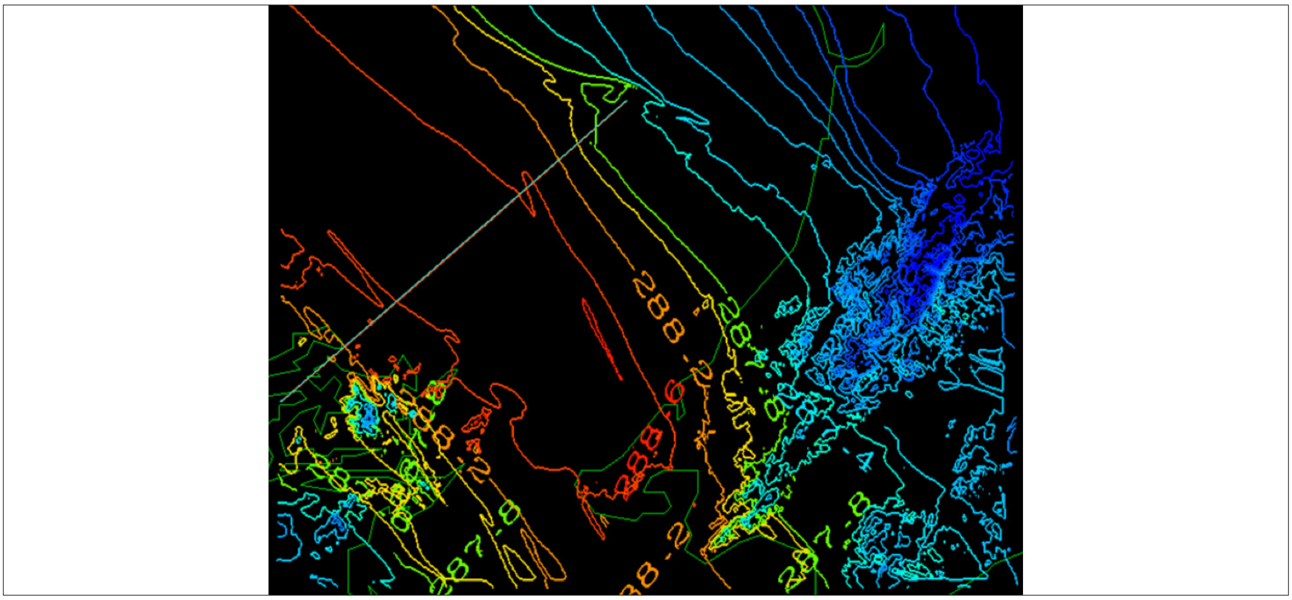

Figure 9: Horizontal slice of Wet Bulb Potential Temperature (°K) at approximately 500 m at 4 am on Thursday 14 May 2015, covering the region of upper South Island, Cook Strait and the lower North Island. The white line indicates the location of the cross section in Figure 12.

potential temperature (WBPT) field at 950 hPa or approximately 500 m above the model's surface, for the region of the upper South Island, Cook Strait and the lower North Island, at 0400 hrs NZST on May 14. This is about the time the bands of heavy rain began over the lower North Island. There is a clear tongue of warm moist air (approx. 288.6 K) being advected at low levels from the northwest onto the lower North Island. This is based on the output from the 1.5 km resolution NZCSM model, initiated at 2100 hrs on May 13 so a T+7hr forecast. Although the details of the convection may not necessarily be correct, the model does appear to give a reasonable description of the larger scale flow as explained in the next section.

3.2 *Vertical section*

In Figure 10 we show the vertical cross section of WBPT

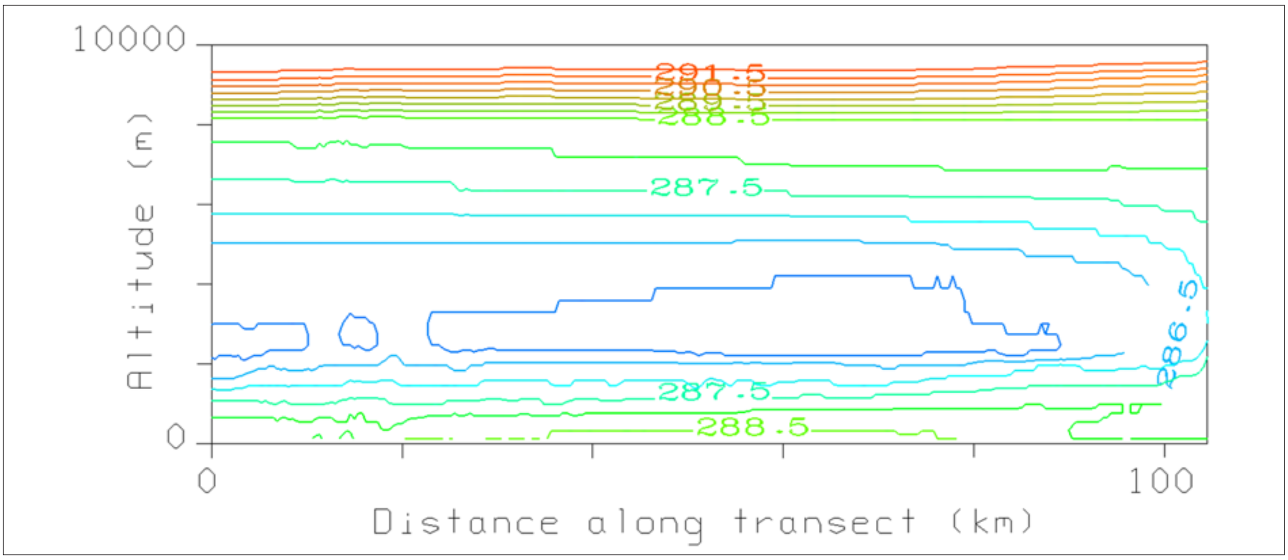

Figure 10: Cross section of wet bulb potential temperature at the location and time indicated in Figure 11. Contours every 0.5°K.

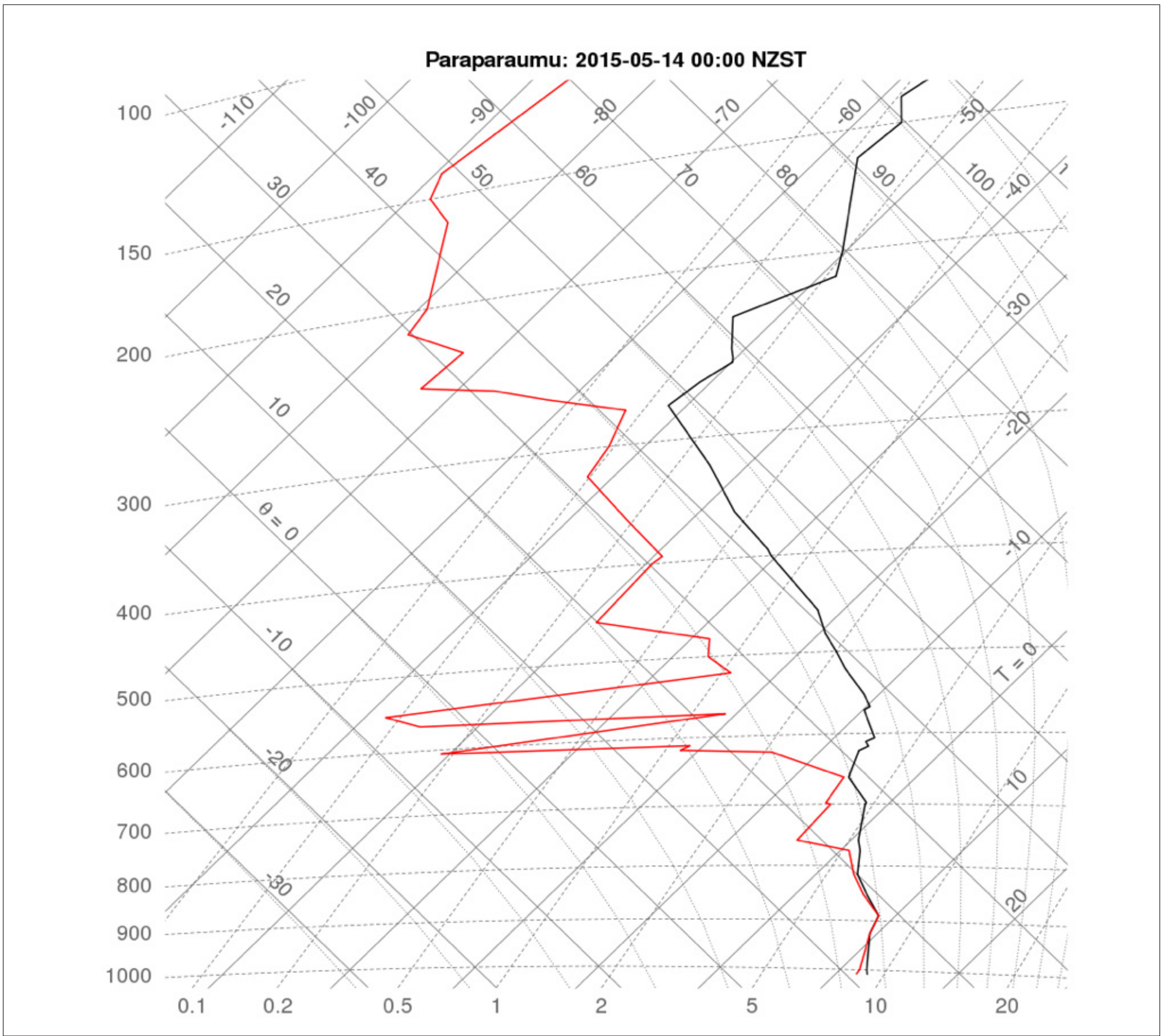

Figure 11: Temperatures and dewpoints from the Radiosonde flight at Paraparaumu Airport at midnight NZST on the morning of May 14. Pressures in hPa on the vertical axis and mixing ratios in g/kg on the horizontal axis.

valid for the same time and along the white line marked in Figure 9 looking to the northwest. It clearly illustrates a layer of unstable air between the surface and about 3 km as the WBPT decreases from about 289 K to 285 K. The layer below 2 km is completely saturated, so this is a moist absolutely unstable layer (MAUL). The larger scale flow, by providing copious amounts of warm moist air at low levels, appears to be destabilising the atmosphere at a faster rate than it can be released by convection. This is supported by the temperature and dewpoint observations from the radiosonde flight at Paraparaumu Airport at midnight NZST on the morning of May 14 shown in Figure 11. There is a clear MAUL between 800 and 900 hPa (approximately 1 and 2 km). The significance of this is described in Bryan and Fritsch, (2000). They suggest the properties (e.g., depth and intensity) of the MAUL may help explain the variations in the cellular structure of the convection that occurs. In the presence of a MAUL, rather than the convection being in the form of an ensemble of discrete cumulonimbus towers, it may be possible for it to have the larger scale more banded structures, as is observed in this case.

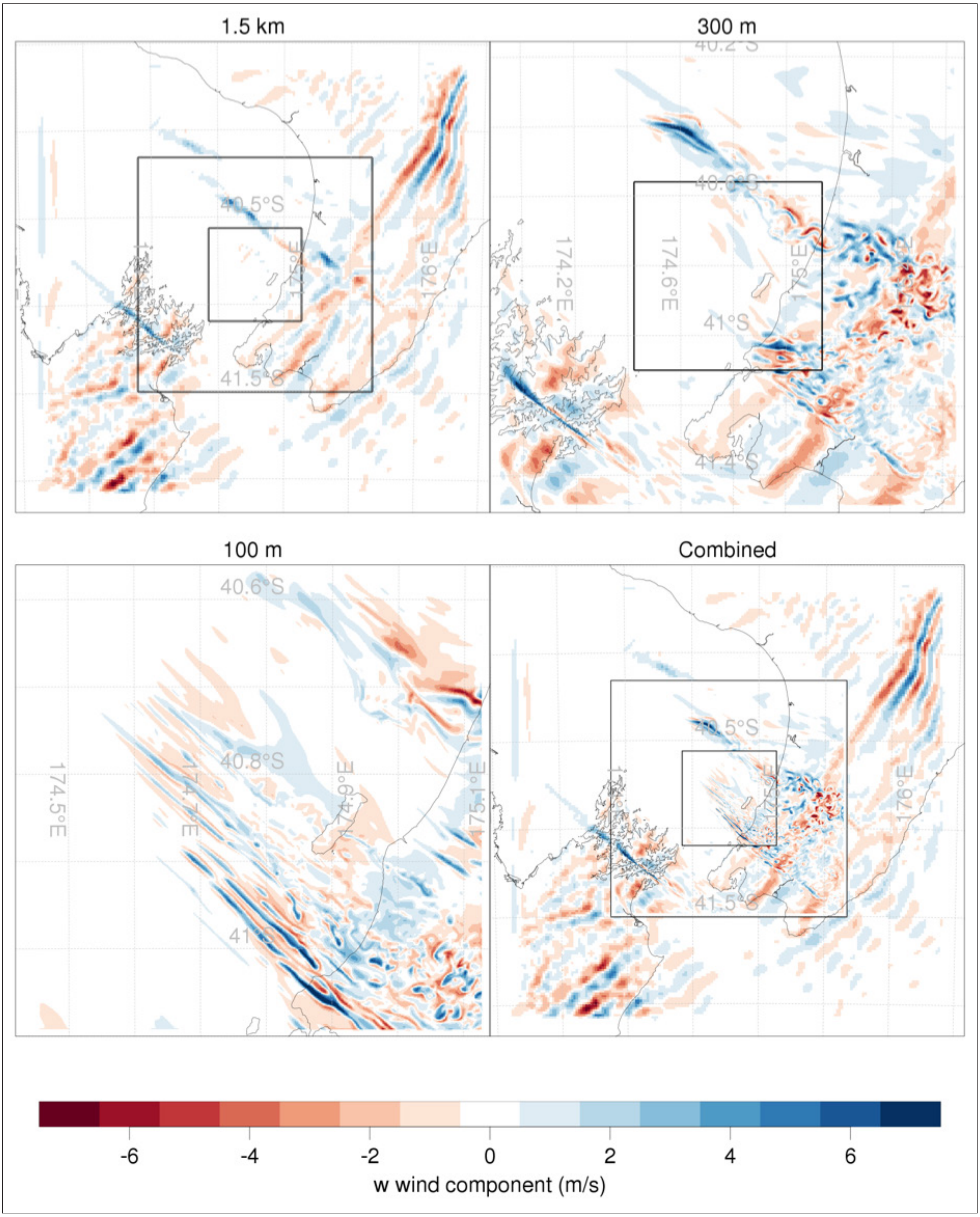

Figure 12: Vertical velocity valid at 5:10am on May 14 at 1605 m above the model surface on the 1.5 km, 300 m and 100 m grids. Black boxes on the 1.5 km and 300 m domains indicate the extent of the nested sub-domain(s). The lower right panel combines all three nested resolutions together.

3.3 Effect of very high resolution on rainband formation

As mentioned in Section 2.4, when compared to rain gauges, model forecast rain totals are generally better as resolution increases from the 17 km grid of the global model down to the 1.5 km grid of the convective-scale NZCSM. The global and regional models did not resolve the convective bands at all. However, although the NZCSM does produce convective bands they tend to be fewer than, larger-scale than and not always in the same location as those depicted in the radar imagery.

Figure 12 shows the rain-band evolution, in terms of the vertical velocity at 1600 m above the model surface, at 0510 hrs on the morning of May 14, 2015, on the 1.5 km, 300 m and 100 m grid spacing nests of the model. The main bands which are produced in the 1.5 km operational run are further resolved in the finer nests, generally with increasing intensity, more structure and smaller scales as resolution increases. On the 300 m grid and particularly on the 100 m grid there are many more shallower bands that are not initiated on the 1.5 km grid. Thus, it is possible that lack of resolution contributed to the failure of the operational 1.5 km run to produce rain bands at the correct locations.

4. Summary, discussion and potential further work

During Thursday May 14, 2015, an active front passed over the greater Wellington region with embedded bands of intense convection and very high rain rates. The front had a northwest to southeast orientation and the winds were predominantly from the northwest so the front moved along its length meaning the intense rainfall associated with organised bands was able to remain in place for much longer than that associated with purely cellular convection. This led to severe flooding with return periods over 100 years in many areas from Waikanae southwards.

The operational NZCSM demonstrated that it is capable of generating maximum hourly rain totals similar to what was observed. Reasonable forecasts were obtained when the rain amounts were below 10 mm/hr as well as reasonable 24-hour totals at all stations except Paraparaumu. However, it failed to predict the high rain amounts above 10 mm/hr at the right place and time at the available rain gauges and also demonstrated high sensitivity to the initial conditions with forecasts initiated 6 hours apart producing significantly different forecasts. Increasing the model resolution from global to cloud scale and removing the parameterised convection scheme mostly leads to improved forecasts and the large differences between the 5% and 95% rainfall forecasts by NZCSM illustrates that this model is capable of producing sharp spatial gradients of extreme convective rain. The banded structure of the rain is captured by NZCSM at 1.5 km resolution, but it appears resolution nearer to 100 m is needed to get the scales correct. These results suggest that the best use of the model output is to express convective type rain in probabilistic terms, and that ensemble methods may be a more appropriate way forward.

An ensemble forecasting study would be the subject of further work into this event, as would an investigation in to the sensitivity of the forecast rainfall to the moisture availability in the incoming airstream.

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