

Improving reliability and quality of rainfall information available during and after extreme events

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Contents

1	Scope and Purpose	1
2	Background to Weather Radar Measurements	3
2.1	Processed Mahia Radar Observations for Hawkes Bay	5
2.2	Risks for HBRC in the use of Wellington Radar Information.....	6
3	Rapidly updating gridded observations using NWP	11
3.1	Data	12
3.2	Method.....	12
4	Results	14
5	Summary and Recommendations	19
6	References.....	21

1 Scope and Purpose

High quality rainfall information is an essential input into local government activities, such as planning and civil defence. The quality (potential errors) in rainfall information also needs to be well understood to minimise risks associated with acting on incorrect information.

During ETC Gabrielle, HBRC's hydrometric system faced challenges, including some failures in rain gauge telemetry, which unfortunately left council staff without real-time rainfall data. Meanwhile, there was no capability to ingest rainfall information from the National Radar network, beyond basic qualitative graphics. The lack of rainfall information proved critical, particularly during the catastrophic flooding experienced in the Esk Valley. While rain gauge data was recovered in the days after the disaster, the underlying resilience risks within the gauge network telemetry system are costly to resolve and cannot be fully guaranteed to work during

future emergencies. Sparse gauge observations are also well understood to have limitations in interrogating spatial variability in rainfall totals, particularly around orography.

Complementary rainfall data sources, which can provide reliable and actionable rainfall information across the region during extreme weather events, are urgently required. In particular, work to understand the potential for better using existing rain gauge, numerical weather forecast data and rain radar observations during emergencies is required.

Weather radar, supported by rain gauge measurements when available, is the best available technology for observing the quantity and spatio-temporal characteristics of rainfall in near-real time. Operational national radar is already provided by the central government for Hawke's Bay in the form of a relatively new radar platform on the Mahia Peninsula. The radar site has backup power and communications and is hardened to withstand natural disasters. The radar operated through the Esk Valley flooding, however no operational rainfall analyses were available at the time as little work has been undertaken at the national level to address science questions about the quality of radar-derived rainfall estimates.

National-radar derived rainfall estimates were provided after Gabrielle by the national forecaster (MetService), however these data have not been critically assessed. Activities in Auckland have demonstrated the MetService automated analyses are typically not of adequate quality for post event analysis or emergency response activities and also have at least a 1-hour time lag. Furthermore, the basic processing is not intended to reliably generate rainfall estimates during rain-gauge network outages. Auckland Council and Northland Regional Council have already identified these risks and invested in a science programme to mitigate these shortcomings, with improved data processing systems for the national radars developed and deployed operationally.

Meanwhile, rain gauge data alone can struggle to characterise rainfall across the diverse topographic settings found in regional New Zealand. Spatio-temporal information about the variability in distribution of rainfall, especially the variability in rainfall due to orographic enhancement, is also available from Numerical Weather Prediction (NWP) outputs. While NWP can have difficulties in predicting the magnitude of rainfall during extreme weather, the underlying spatial information has been successfully combined with rain gauge observations in work at NIWA to improve gauge-interpolated products.

Rain radar (with or without rain gauges), and NWP-supported gauge interpolation methods are thus the core national capabilities for spatially resolved QPE estimates during extreme weather events.

This work assesses the suitability of the science components of the existing Auckland Council rainfall analysis system (based on National Radar data) for the HBRC use-case, and the NIWA rain gauge NWP informed interpolation scheme, by preparing a rainfall analysis from the national radar and HBRC gauge network for the Gabrielle event. Importantly, a leave-one-out cross validation approach has been employed to provide independent cross-validation of both of the rainfall analysis error characteristics. Gaps in the "Auckland Council" method for treatment of radar observations, and the NIWA gauge interpolation schemes, when applied in the HBRC context, have been identified and future work for improvements are proposed.

The feasibility of combining the radar, NWP and gauge analysis methods into an "optimal" framework, resilient to failure of individual components (radar, gauges, NWP), is also discussed.

2 Weather Radar Measurements

2.1 Background

Radar is an active remote sensing technology which illuminates targets with electromagnetic energy and measures the properties of the reflected (or “back-scattered”) radiation to infer the physical properties of the targets.

In the case of meteorological (“weather”) radars, repetitive pulses of electromagnetic energy are focused into the distance by a parabolic antenna (or “dish”). By scanning the dish and recording the bearing and time taken for pulses of energy to return, the familiar maps of precipitation location and intensity can be constructed. The pulse duration determines the radial depth of the sampling volume and the dish diameter determines the angular width of the sampling volume; larger dishes produce narrower beams.

In New Zealand, MetService radars are configured to perform a full scan cycle every 7.5 minutes; a single scan (complete 360° rotation of the radar dish) takes about 30 seconds. The dish elevation angle is then increased after each scan and measurements of radar reflectivity are obtained at increasing altitudes over the 7.5-minute period.

The fundamental radar measurement is reflectivity (Z , units of mm^6m^{-3}), which for meteorological applications is the total scattering cross section per unit volume of all the targets in the radar sampling volume at a particular range:

$$Z = \int_0^{\infty} D^6 N_v(D) dD \quad \text{(Equation 1)}$$

where D is the drop diameter (mm) and N_v is the number of drops with that diameter per cubic metre. Reflectivity is usually expressed in decibel units ($\text{dBZ} = 10 \log Z$), and values typically range from 20 dBZ for light rain to 55 dBZ for very heavy rain. Values over 55 dBZ are likely to indicate solid precipitation (hail).

The total scattering cross section, and hence reflectivity, depends on the (usually unknown) raindrop size distribution, and must be converted to rainfall rate (R , mm hr^{-1}) to be useful for engineering applications.

Other factors influencing the estimation of rainfall which must also be taken into account are attenuation (both due to intervening rain and to water adhering to the radar’s protective dome - “radome”), ground clutter (unwanted echoes of the ground surface) and losses due to signal processing of Doppler ground clutter filters (to mitigate the effects of ground clutter), beam blocking (reduction of echo strength due to intervening terrain), variability in the vertical profile of reflectivity, spatial smoothing and time intermittency of the radar measurement.

Comparison with a local network of rain gauges is typically undertaken as a final processing step to account for variability in the raindrop size distribution and other uncertainties.

Significant care must be taken to correctly treat radar data, known as Quantitative Precipitation Estimation (QPE), for modelling applications. Experiences of Auckland Council Healthy Waters

Department in the use of rain radar data can provide some useful guidance for other New Zealand-based local government end-users that are considering the use of rain radar information. Inadequate quality control and insufficient data processing from the MetService radar’s built-in software previously resulted in data which was unusable for wastewater modelling applications (Milsom et al. 2007). However, improved data processing developed for Auckland Council has culminated in the capability to automatically prepare high quality radar data sets (Fordham et al. 2022), which can be deployed by council staff in modelling workflows (Islam and Tay 2022).

The components of the Auckland Council rainfall analysis system aim to advance from raw rainfall observations towards an optimal QPE analysis, systematically correcting for instrument bias. Modules include: retrospective radar calibration, correction for losses within the microwave and signal processing system (such as Transmit / Receive cell range biases), suppression of return from terrain (ground clutter), variability in the reflectivity profile aloft, the unknown Z-R relationship, sampling and intermittency. Since not all systematic biases can be directly estimated, assumptions are required and a final gauge adjustment step based on Ordinary Kriging of Radar Errors (OKRE) is applied to reduce residual bias and scatter. A diagram of the radar QPE workflow is provided in Figure 1.

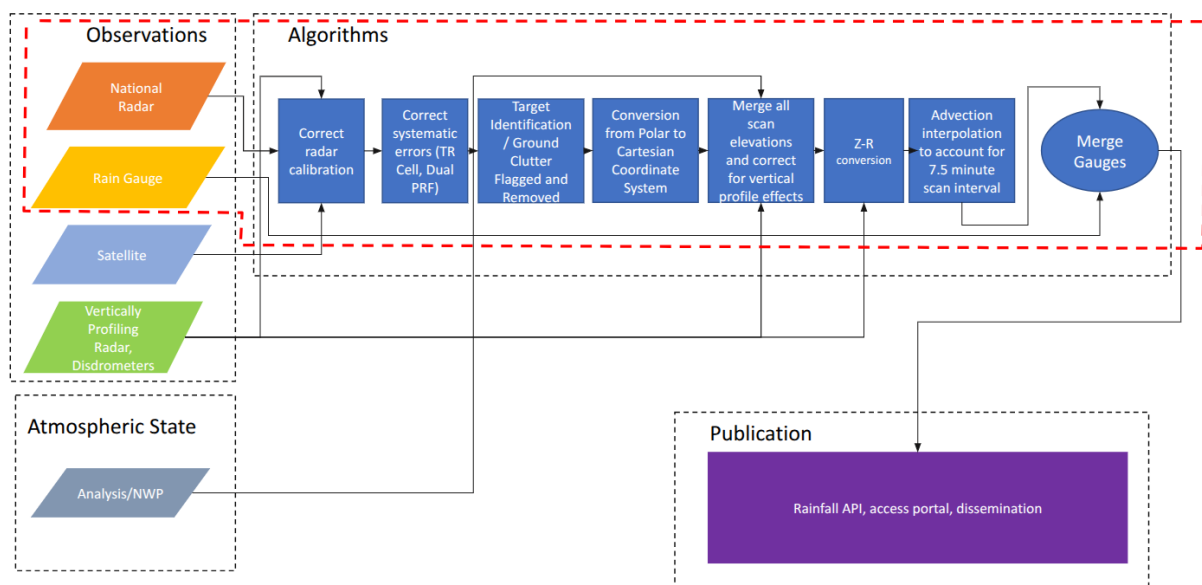


Figure 1: Block diagram for an ideal radar QPE system. The core modules outlined in red have been implemented for this work, based on the Auckland Council operational system.

The QPE system generates robust analyses, for example Figure 2 provides an example of a rainfall accumulation map for the August 2022 Kumeu flooding event. Two gauges in the highest rainfall area were flooded mid-event, further highlighting how the improved radar QPE system contributes to a reliable understanding of the spatial distribution of rainfall patterns in the Auckland region.

The radar QPE developed for Auckland Council has been extensively cross validated against the rain gauge network. This relies on a “leave one out” methodology, where individual rain gauges are withheld from the radar QPE production and used for validation. Statistics are developed by progressively excluding each of the gauges in the network. Figure 3 provides cross-validation

statistics for 24-hr accumulations for a 1-year period incorporating all valid rain gauge measurements from the Healthy Water’s gauge network.

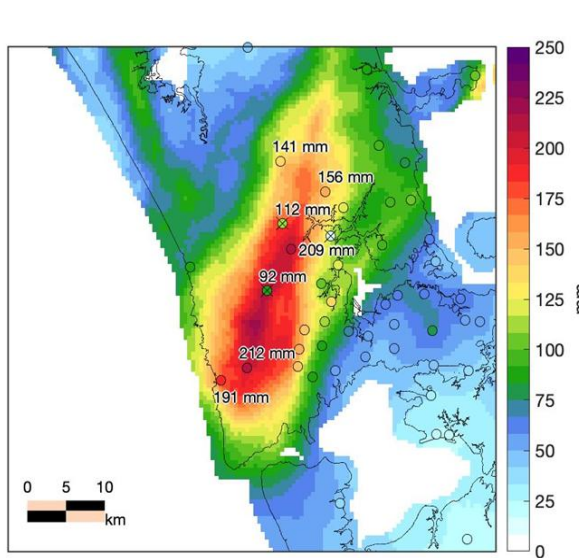


Figure 2: Auckland Council radar QPE and rain gauge depth during the 30 August event (x marks indicated gauges which failed mid-event).

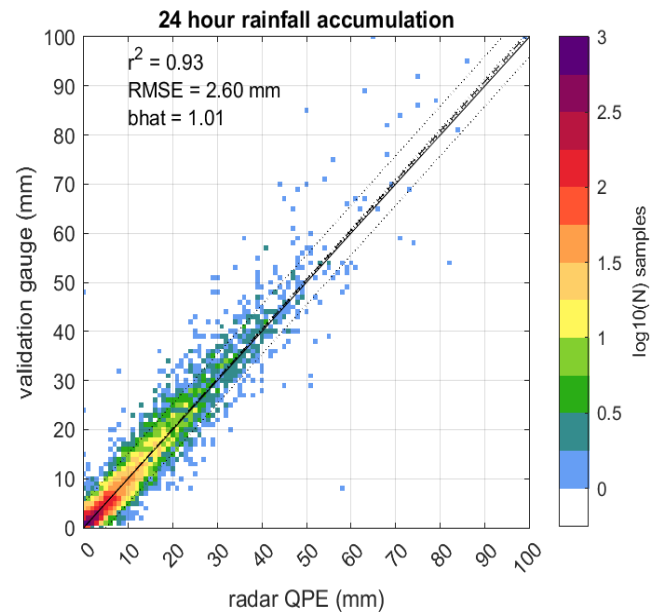


Figure 3: Leave-one-out cross-validation results for the Auckland Council radar QPE system utilizing all Healthy Waters tipping bucket gauges for the period March 2021-March 2022.

Similar radar data processing workflows (employing the same data processing backend as the Auckland Council Healthy Waters system) have also been operationalised in Northland, Wellington and Otago.

2.2 Processed Mahia Radar Observations for Hawke’s Bay

Considering the successful deployment of the radar data processing workflow in other regions in New Zealand, there is interest in investigation of the suitability of the same system for the East Coast, in particular the Hawke’s Bay region.

The nearest weather radar to Hawke’s Bay is situated immediately to the North on the Mahia Peninsula. The radar platform is a dual polarisation C-band system of standard design operated competently by MetService. The data currently available from the Mahia radar is similar to that obtained by the Auckland radar, with the added benefit of dual-polarisation capability. In principle, the radar analysis methods developed in Auckland can be ported directly for the Mahia Radar, with the improved ground clutter suppression capabilities afforded by dual polarimetric measurements.

Raw radar observations were sourced from MetService Ltd, and gauge data, combining all HBRC, GDC, BOP, NIWA and MetService rain gauges were extracted from clidb. Radar data was treated with the standard operational data processing system (e.g. Figure 1), gauge adjustment was applied with both 1 hour and 24-hour windows. The gauge adjustment step was iterated in a leave-one-out approach, to allow independent validation statistics to be obtained.

2.3 Risks for HBRC in the use of Mahia Radar Information

There are some additional risks in using radar information in HBRC compared to Auckland.

Much of -Hawke's Bay is at longer range from the Mahia radar station (up to 175km) compared to the Auckland urban area (which is only ~70km from the radar) and Wellington (

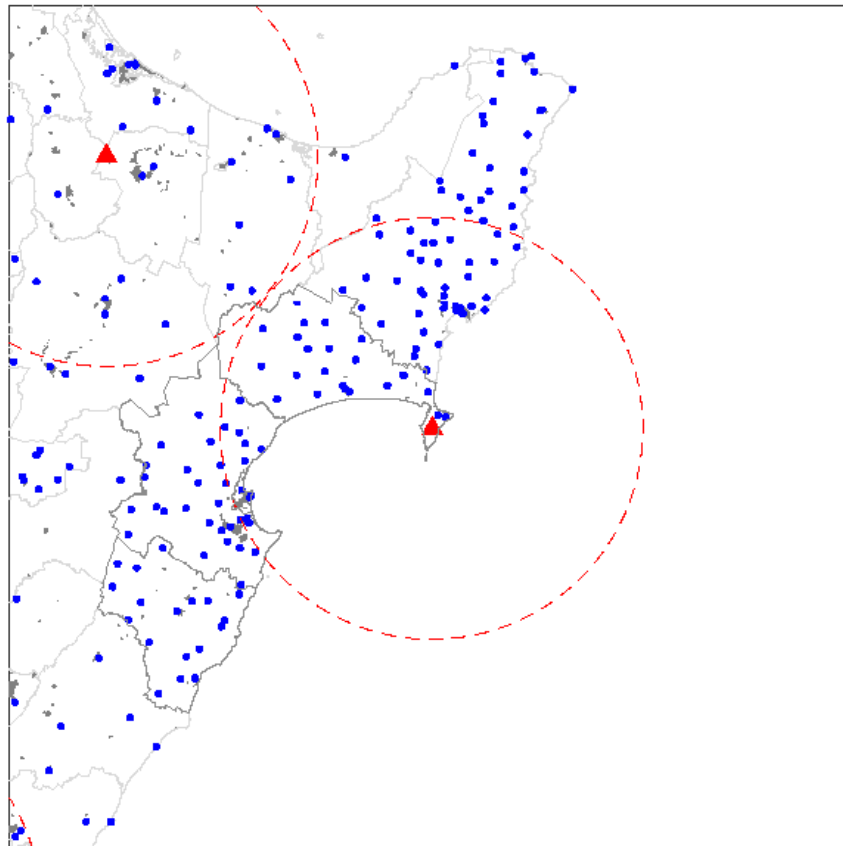


Figure 4). Analysis of weather radar observations are well known to be more complex at longer ranges, given the progressively increasing sampling volume and altitude, along with more severe attenuation due to intervening rain. Although numerous urban areas in New Zealand are over 100 km from the nearest MetService radar (e.g., Kaikoura, Westport, Hastings, Wanganui), little work has been undertaken in the New Zealand context to systematically explore the limits of the MetService radar network for hydrology at longer ranges. This is almost certainly because the main centres of innovation (Auckland and Wellington) have radars at much closer distances. Therefore, there have been no robust assessments of radar data at longer range.

The principal risks associated with use of the Mahia radar information for the generation of precipitation estimates in and around -Hawke's Bay (and indeed, the Gisborne/Tairāwahiti) relate to unexplored uncertainties in the relative performance of the radar system (in comparison with Wellington and Auckland), which arise due to A) use of the radar observations at longer ranges and B) unknown overall calibration of the radar platform.

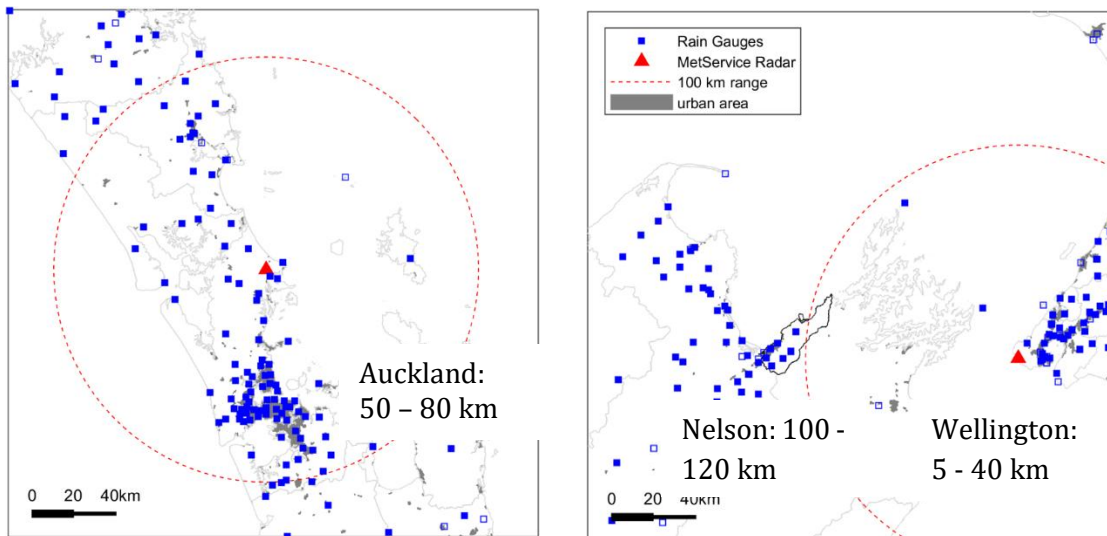
Sources of uncertainty related to range effects can be summarised as follows:

- 1) Geometric

Weather radar samples a conical volume of atmosphere extending from the radar site. The beam of the MetService radars is about 0.9° wide, so the horizontal and vertical extent of the sampled volume increases with range. The curvature of the Earth also causes the beam to climb upwards relative to the surface as the radar beam propagates from the radar site, though this is slightly mitigated by refraction due to temperature and humidity gradients in the lower atmosphere.

An opportunistic solar antenna alignment method (where radar detections of emissions from the sun are compared to astronomical tables) was first employed to verify the Mahia radar was level and quantify any systematic encoder errors.

A minor Azimuth pointing error of 0.25 degrees ($1/4$ of a beam width) was detected (Figure 5). The radar plinth about which the radar dish rotates is also not entirely level, the radar dish points slightly low to the west and slightly high to the east (0.07 degrees). The error is relatively small but amounts to height errors at longer range (altitude error 250m at 200km range). In any case the biases are corrected in subsequent processing and in an operational system can be monitored for any changes.



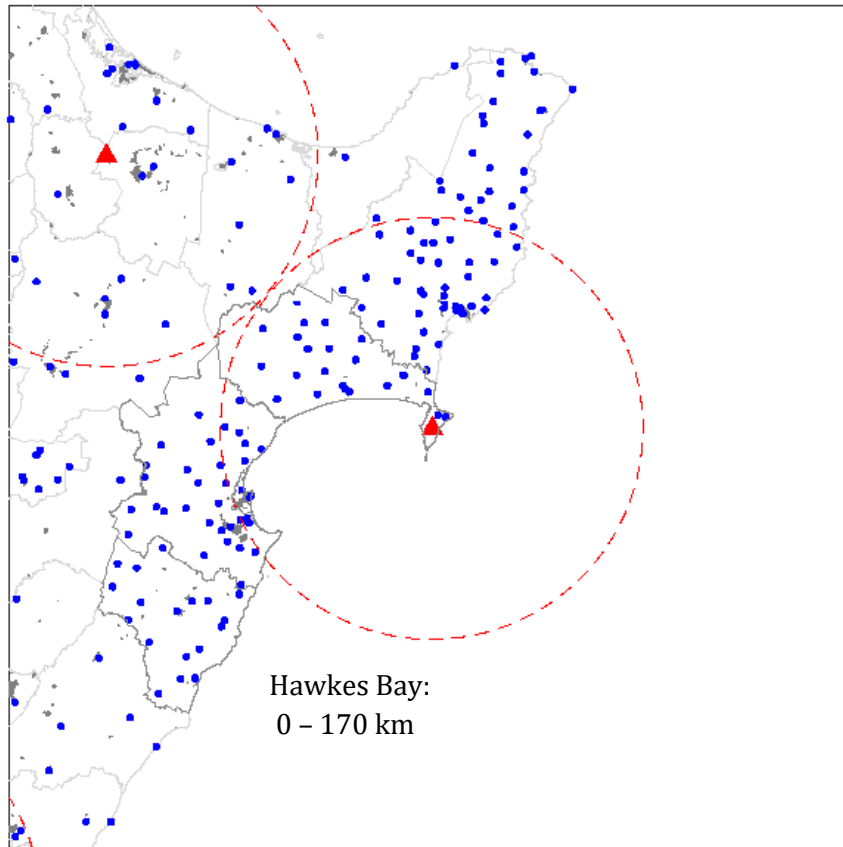


Figure 4: 100 km radar range circles for the Auckland (top left), Wellington (top right) and Mahia (bottom) MetService radar stations. Approximate distances between the radar station and areas of interest are indicated.

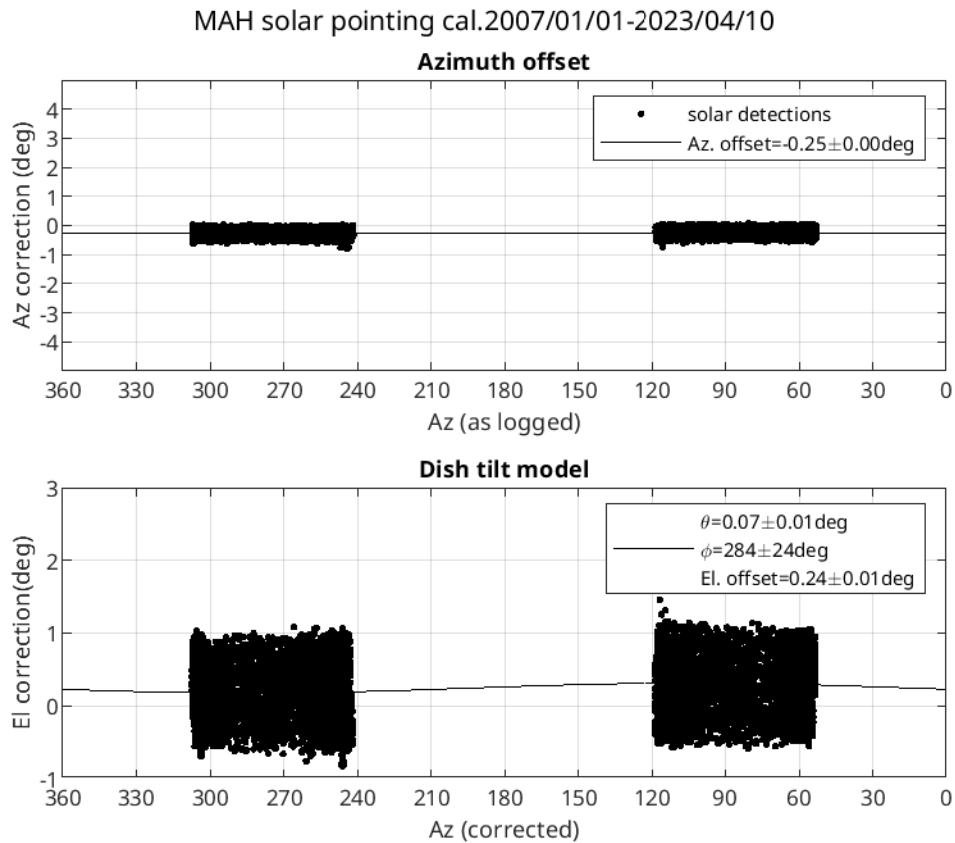


Figure 5: Antenna point errors in Azimuth and Elevation for the Mahia Radar.

After correction for antenna point errors, the anticipated sampling volumes of the Mahia radar can be determined by ray tracing from the radar site. Figure 6 provides the minimum altitude visible to the radar, while Figure 7 provides an indication of the region of the atmosphere sampled above the Esk valley.

The key geometric characteristics apparent from Figure 6 and Figure 7 are as follows:

- The radar beam width is about 2km over the Esk Valley, and larger at longer range.
- There is partial beam blocking of the lowest elevation scan at some azimuth angles due to intersection with terrain.

a) Beam Blocking

Beam Blocking occurs wherever the radar beam intersects terrain. In practice, partial beam blocking can be overcome either by geometric calculation of the expected power losses due to intersecting terrain followed by application of appropriate corrections in the data processing stage, or by use of the next-highest radar scan. In this case, because terrain is relatively distant from the Mahia radar beam blocking not a major problem.

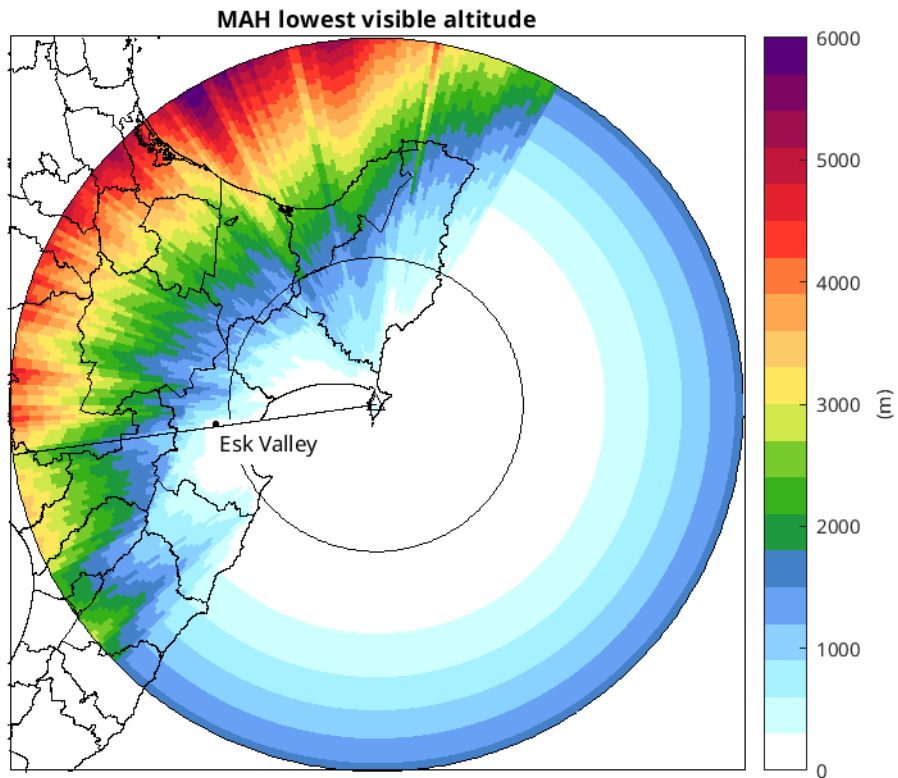


Figure 6: Minimum visible altitude for the Mahia radar site.

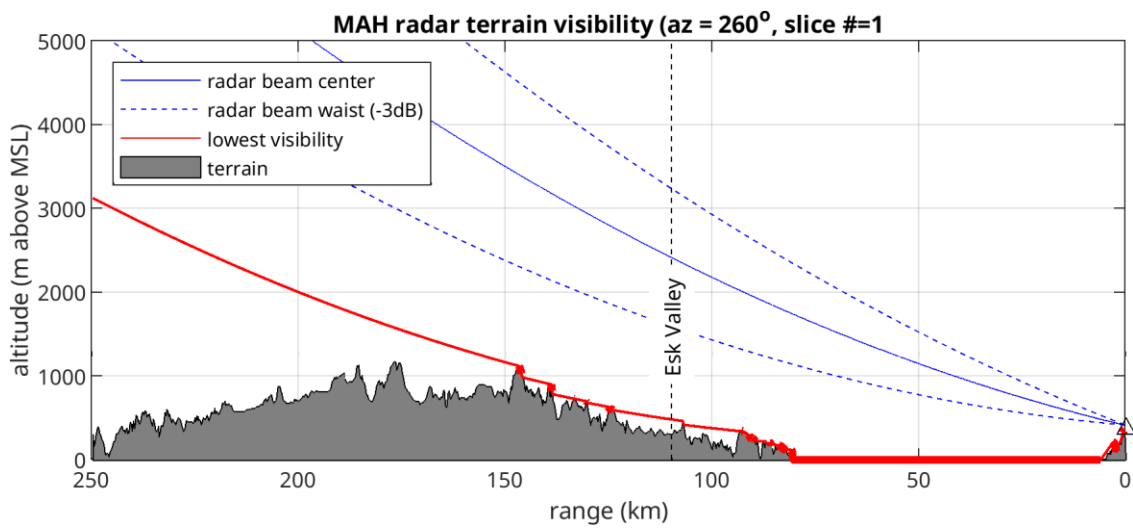


Figure 7: Vertical cross section from the radar site over the Esk Valley. The radar beam waist and approximate vertical extent (beam waist) for the lowest operation antenna scanning angle are plotted (taking into account the dish tilting). The lowest visible altitude and visible terrain and the ocean surface are also indicated in red.

b) Beam spreading, overshooting and freezing level effects and orographic enhancement.

A more difficult problem to overcome is the comparatively large beam width and altitude of the sampling volume. The higher altitude of the sampling volume, in comparison with similar applications in Wellington and Auckland, will for any operational radar QPE system increase the fraction of rain events for which the radar beam will intersect the freezing level (the altitude at which the temperature drops below 0°C) or overshoots the rain entirely.

Radar observations of precipitation within the freezing level are typically dominated by signals from melting snow, which results in a characteristic “bright band” pattern emerging in the radar images. This typically results in an over-estimation of rainfall rates, if uncorrected or before correction with local gauge data.

Overshooting of rain can result in the radar not detecting rain at all, although this is usually more problematic for light rain events which tend to be shallower.

Neither of these effects has been well investigated in the New Zealand context because the situations are largely avoided in the Auckland and Wellington radar data processing workflows. In Auckland, a warmer sub-tropical climate results in a larger proportion of deep rain events allowing most radar measurements to be made below the freezing level, even at 100km range. In Wellington, the proximity of the radar site to the greater Wellington urban area also means only observations are typically made below the freezing level.

For ETC Gabrielle, flows were relatively warm and the freezing level is between 3000 and 3500m. This means that for much of the Hawke’s Bay region, observations are made at least partially in snow and ice aloft. These effects are partially overcome by the vertical profile correction module.

A more critical systematic bias for QPE derived from radar observations of ETC Gabrielle is the lack of low-level information around terrain. Orographic enhancement of rainfall occurs when low level clouds form over terrain in moist saturated and neutral stability conditions—such as outflow from ETCs. When low-level orographic clouds form efficient scavenging of cloud vapor by raindrops from aloft can result in significant growth of rainfall in the lowest 1km of the atmosphere. This effect was observed for ETC Gabrielle by a vertically profiling radar operating in the Waitakere Ranges and enhancements of up to 10dBZ were observed, which corresponds to about a 4x increase in rain rate around topography. The operational QPE system deployed here does not attempt to estimate orographic enhancement, this means radar QPE results significantly under-estimate rainfall totals before gauge adjustment, particularly around topography.

2) Attenuation

Electromagnetic waves at the wavelengths employed by the MetService radar (~5.4cm) are moderately attenuated by liquid water, both in the form of rain adhering to the radar stations’ protective dome (radome) and intervening rain between the radar station and Nelson.

a) Attenuation due to Radome Wetting:

Most larger radar antennas (including the Mahia radar dish which is some 2.4m in diameter) are protected from wind and rain by a radome. While essential to avoid excessive wind loading on the radar dish, radomes absorb a small fraction of the radar signal. However, when

the radome is wet the losses can be more significant. The effect of radome wetting for the class of radomes employed by NZ MetService on the Auckland and Wellington radars has been quantified by inter-comparison with Vertically Profiling Radar measurements during a field study (May – October 2019) according to the methodology described by Frasier et al. (2013). Although these losses are not insignificant (accounting for losses of up to 25% in heavy rain) radome wetting errors are mitigated in real-time based on the estimated rainfall intensity immediately around the radar site. However, the correction algorithms require further validation.

b) Path Integrated Attenuation (PIA)

Path Integrated Attenuation correction is implemented in the radar software after Bringi et al, (2001), however assessment of the effectiveness of the corrections have not been validated. Comparisons with Vertically Profiling Radar will be undertaken, initially in the Wellington region, to characterise and optimise attenuation corrections using dual-polarisation observations in a New Zealand context.

3) Wind Drift

Rain drops attain a terminal velocity which depends on the ratio of their volume to surface area, with larger drops experiencing proportionately less drag and hence falling faster. Most rain falls at a terminal velocity of between 4-6ms⁻¹. Considering the altitude of the MetService radar beam over Hawke's Bay (Figure 7), typical fall times are of the order 10 minutes. Based on this fall time, even moderate wind speeds can result in significant displacement of the rain observed by the radar before it reaches the ground. Wind speeds during Gabrielle were high so displacement by many kilometres is possible but has not been assessed here.

3 Rapidly updating gridded observations using NWP

This section describes a method of estimating near real-time gridded rainfall without the use of rain radar observations. Instead, only telemetered rain gauge observations and recent numerical weather forecast predictions of rainfall are combined to produce spatial estimates of hourly rainfall with a grid length of about 2 km.

With access to reliable rain gauge observations, this becomes an interpolation problem. So, to produce accurate estimates of rainfall rates at ungauged locations additional spatial information is required.

NIWA's standard Virtual Climate Station Network (VCSN; Tait et al., 2006) uses a climatological surface (mean annual rainfall) to provide information to guide interpolation between gauges. This works reasonably well for longer time scales, for example, monthly rainfall or, in certain circumstances, daily rainfall. However, for unusual or extreme events where the spatial pattern of the observed rainfall may not match the long-term average, this method produces poor results (Mullan and Sood, 2023). This is also true at the hourly scale, where the mean annual rainfall surface rarely matches the spatial pattern with a high degree of skill.

Numerical weather prediction (NWP) forecast fields provide spatial information that aligns with the weather of the day. This makes it a more useful source of detail for unusual events and shorter time scales. However, NWP forecasts are not perfect and come with their own biases and spatio-temporal errors which need to be corrected if they are to be used as estimates of near real-time rainfall.

When rain gauge observations are available, forecast biases can be corrected by “anchoring” the forecast to the observations at gauge locations. The known errors at gauge locations can be used to adjust the forecast not only at those locations but can also be used to adjust the full NWP grid. While this will help reduce the forecast bias, it will not compensate for spatio-temporal forecast errors, for example if the timing of a frontal passage is wrong or the location of convective showers is incorrect. The magnitude and frequency of these type of errors is greatly reduced when forecast fields have been aggregated over a longer time period such as 24 hours.

To incorporate both of these solutions, the final hourly rainfall grid is created in two main steps. First a 24-hour aggregated NWP field is combined with 24-hour observations to produce an unbiased rainfall field with the best possible spatial representation. This 24-hour surface is then disaggregated to hourly resolution using the temporal patterns from rain gauge observations.

3.1 Data

NIWA runs several numerical weather prediction (NWP) systems which all utilise the UK Met Office Unified Modelling system and this study has focussed on two of them. Firstly, the New Zealand Convective Scale Model (NZCSM; e.g. Cattoën et al., 2016) is a 1.5 km convection permitting model that is updated 4 times per day and is driven from boundary conditions created from NIWA’s 4 km, data assimilating limited area model (NZLAM). NZCSM is a deterministic model, in that it only provides one realisation of the next 2-days of weather each 6 hours. The second model used is NIWA’s ensemble system, NZENS, which is also updated 4 times per day, but runs at a slightly lower 4 km resolution. However, this model is driven from boundary conditions provided by the UK Met Office Global ensemble model (MOGREPS-G) and provides 18 different realisations of the next 6 days of weather from each forecast cycle. The ensemble provides users of the forecast with both a best estimate of the future weather as well as information about the forecast uncertainty and range of likely outcomes. On average, the ensemble mean forecast outperforms any of the individual members.

Data from both of these NWP systems was trialled in the project to assess whether the added spatial detail provided by the higher resolution NZCSM led to that model providing the best results or whether the multiple realisations from NZENS led to the ensemble system doing a better job of capturing the true spatial outcome of the rainfall event.

For this analysis, hourly rain gauge data from NIWA’s Climate Database was augmented with records provided by Hawke’s Bay Regional Council and Gisborne District Council that covered the time-period ex-TC Gabrielle impacted the North Island’s east coast.

3.2 Method

A semi-automated process has been developed to mimic how a real-time operational system would run (excluding an automated step to ingest council observations) and is depicted by the flow diagram in Figure 8. It is envisaged that such a system would be triggered once every hour with a delay included to ensure most real-time gauge observations are available for ingestion. Once triggered the system takes about 10 minutes to complete at which time the resulting outputs could be disseminated to interested parties.

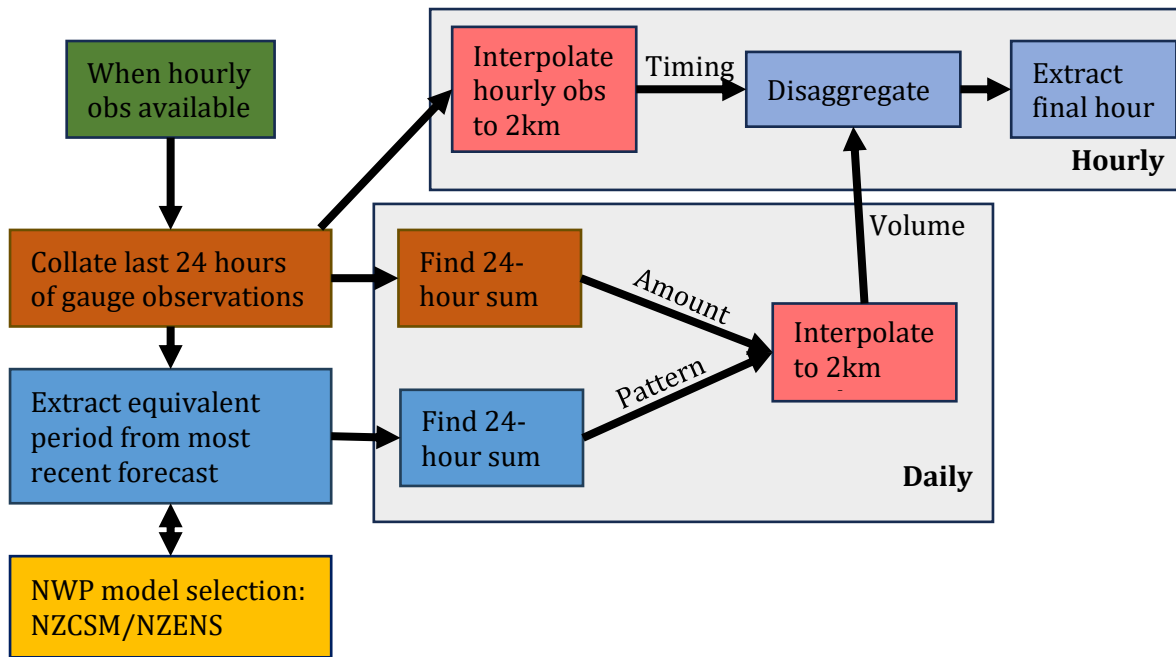


Figure 8: Flow chart describing methodology used to generate hourly rainfall fields from gauge observations and NWP forecasts.

Both interpolation steps, hourly and daily, are performed using ANUsplin, a thin plate spline software package developed at the Australian National University (Hutchinson, 1984). For the daily step, the thin-plate spline uses two spatial independent variables (easting and northing) with additional spatial information from the NWP model incorporated as a covariate. For the hourly step, the spline only uses the two spatial independent variables.

To enable a comprehensive analysis and comparison with the radar QPE product, a leave-one-out cross-validation was performed at each timestep. This simply involves withholding the observations from one rain gauge at a time during the processing before predicting the rainfall value at that location. This enables the model to be assessed using all available gauge observations, as if those gauges were not available to be used for bias correction.

4 Results

Quantitative Precipitation Estimates (QPE) derived from the merged radar-gauge (Section 2.2 page 5) and VCSN-NWP (Section 3.2 page 12) methods were prepared for the time period covering the rainfall from ETC Gabrielle (12 February 12:00 to 14 February 00:00 UTC). The MetService radar power failed on 14 February at approximately 00:45 UTC, so no radar data was available after this point, however it is noted that this is well after the main rain event.

The radar QPE product is generated on a 768x768 pixel grid (500m pixel resolution) centred on the Mahia radar, and covers all of Hawke's Bay and much of Gisborne/ Tairāwhiti and the Eastern BOP. The VCSN products are national in extent, so to ensure comparability of the leave-one-out cross validation methods, VCSN results were trimmed to the radar QPE grid and interpolated with a nearest neighbour method onto the radar QPE grid.

An example of 24-hour accumulation fields for each product from the peak period of the event is provided in Figure 9. Notably, all three QPE products capture similar spatial patterns and identify high rain areas around orographic features.

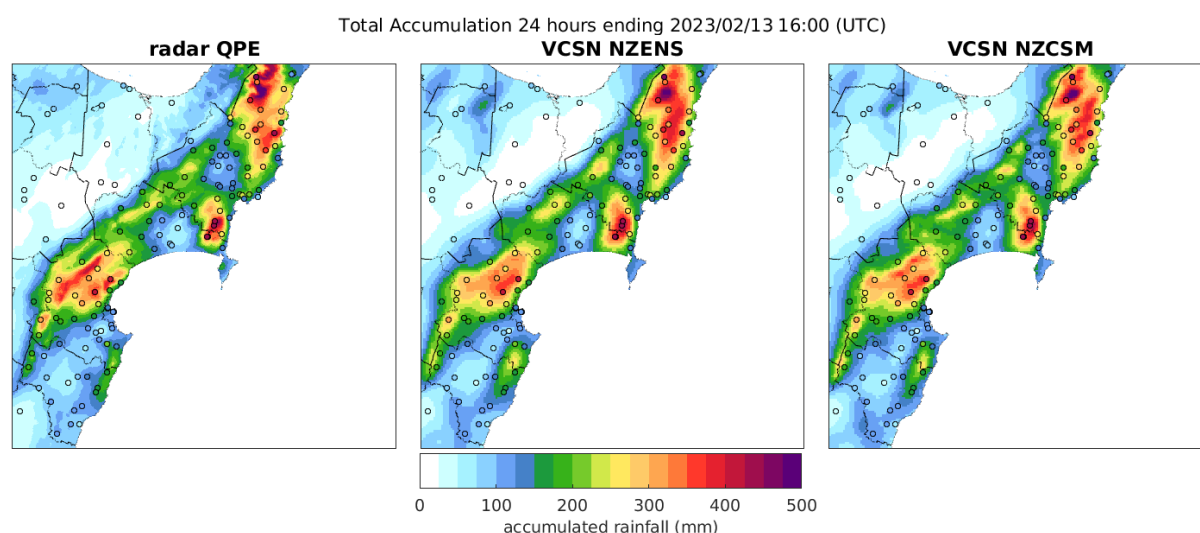


Figure 9: An example of 24 hour rainfall maps for the merged radar/gauge (left) and merged NWP/gauge (middle and right plots) analyses.

1- and 24-hour accumulations were prepared at 1-hour intervals, and cross validation estimates at each gauge location, for each QPE type, were prepared as described earlier. Figure 10 provides an example of data extracted from the cross validation process for the same 24-hour window as depicted in Figure 9. Cross validation results are all characterised by increasing scatter for larger depths, and as total depth increases the chance of the QPE product under-estimating total depth increases (see outliers in the lower left quadrant in Figure 10).

Statistics calculated in Figure 10 were from the highest accumulation time period during the event. Figure 11 summarises validation statistics for a moving 24-hour window over the entire event. Initially, RMSE is lower because the accumulated rainfall is lower in earlier time windows. The radar QPE and VCSN methods generally perform similarly up until about 01:00 13 February UTC, and then the radar QPE performance degrades slightly compared to the VCSN methods.

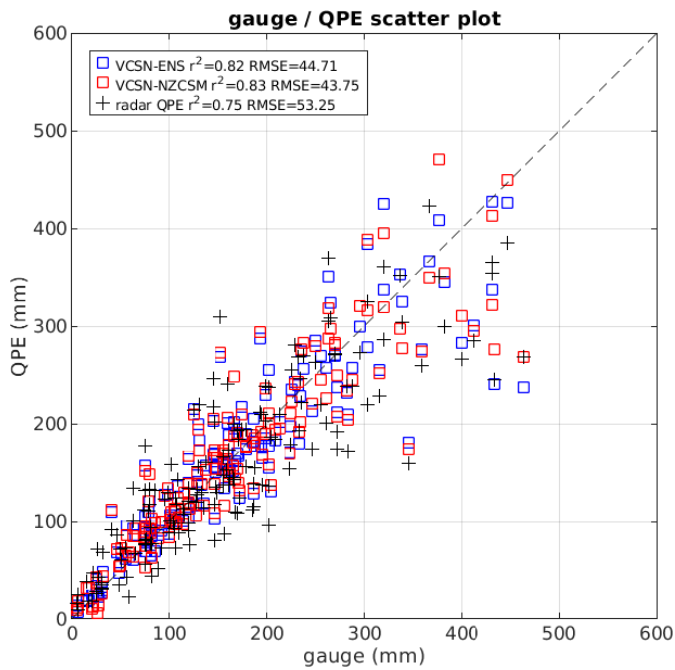


Figure 10: Example cross-validation scatter plot and statistics for the same time period (UTC) as in Figure 9.

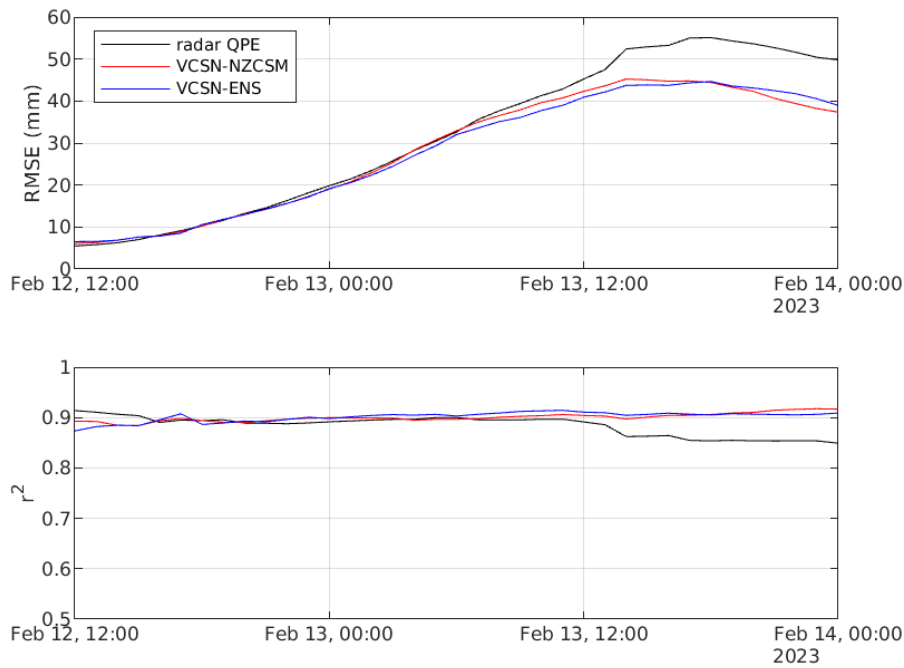


Figure 11: 24-hour validation statistics (RMSE and r^2) for the radar QPE, VCSN-NZCSM and VCSN-ENS products.

Cross validation accumulation traces were also prepared from the 1-hour data for a selection of rain gauges in and around the Esk Valley (Figure 12 to Figure 16). For each gauge, the cross-validation QPE product, and the underlying raw QPE raw data before gauge adjustment, are compared with the validation gauge.

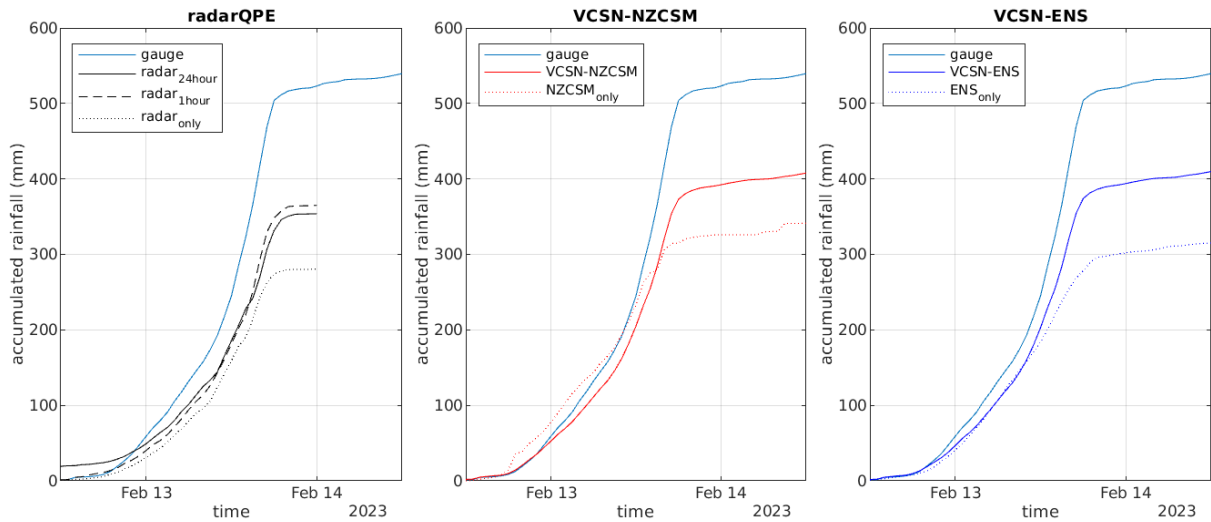


Figure 12: Cross-validation accumulation traces for the radar QPE (left) and NWP based QPE products (middle and right panels) at the Glengarry gauge.

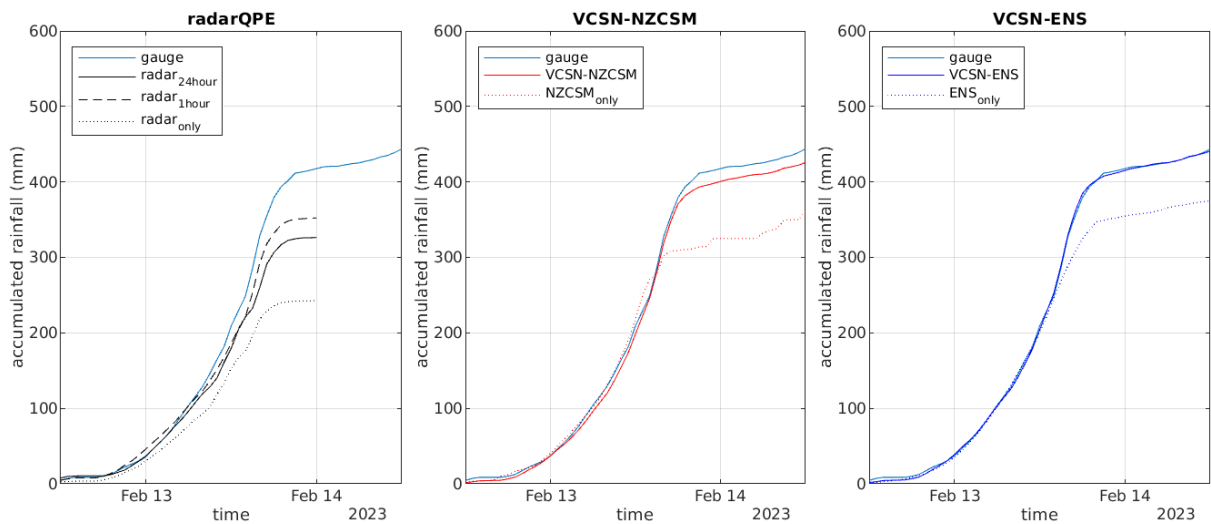


Figure 13: Cross-validation accumulation traces for the radar QPE (left) and NWP based QPE products (middle and right panels) at the Te Pohue No.2 Climate station.

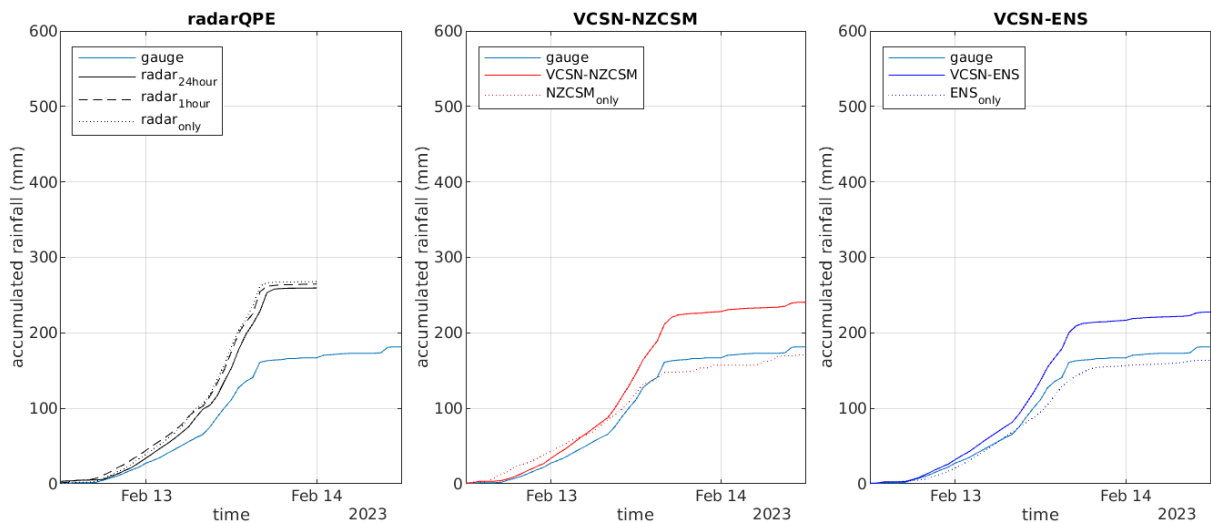


Figure 14: Cross-validation accumulation traces for the radar QPE (left) and NWP based QPE products (middle and right panels) at the Waipatiki gauge.

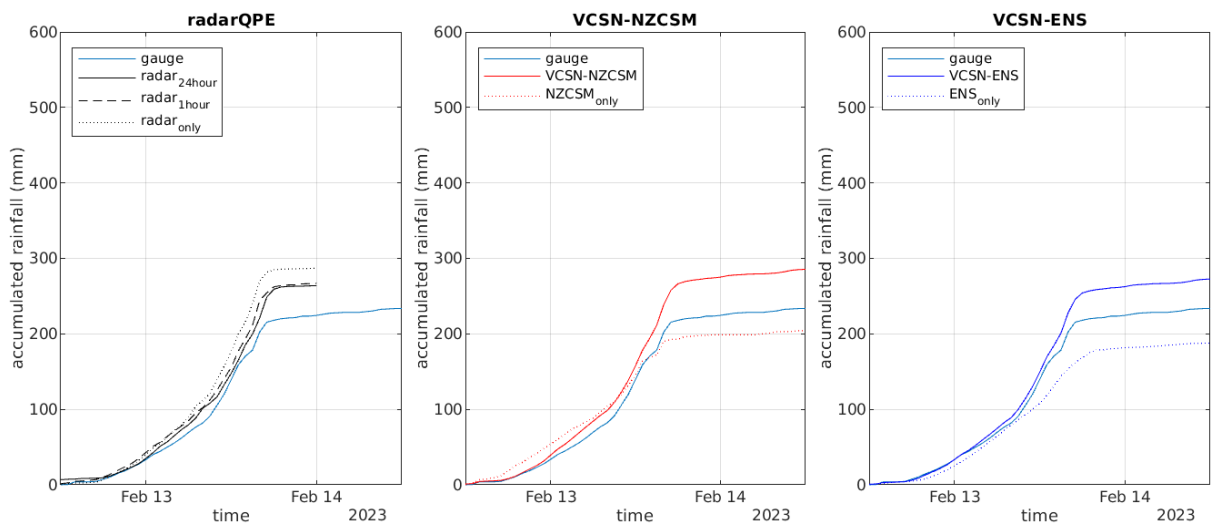


Figure 15: Cross-validation accumulation traces for the radar QPE (left) and NWP based QPE products (middle and right panels) at the Fishers gauge.

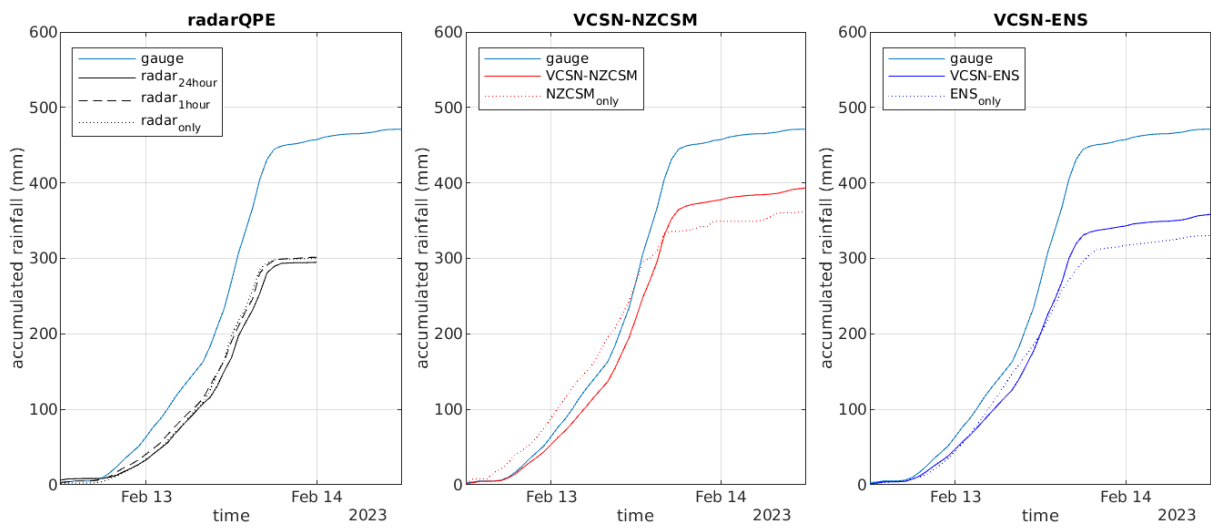


Figure 16: Cross-validation accumulation traces for the radar QPE (left) and NWP based QPE products (middle and right panels) at the Kaiwaka Tareha Climate climate station.

4.1 Data denial experiments

Infrastructure damage due to high winds associated with Gabrielle caused telemetry to be interrupted for many sites in the HBRC rain gauge network, significantly reducing rainfall observation availability during the event. Gauges for which telemetry were interrupted are indicated in Figure 17.

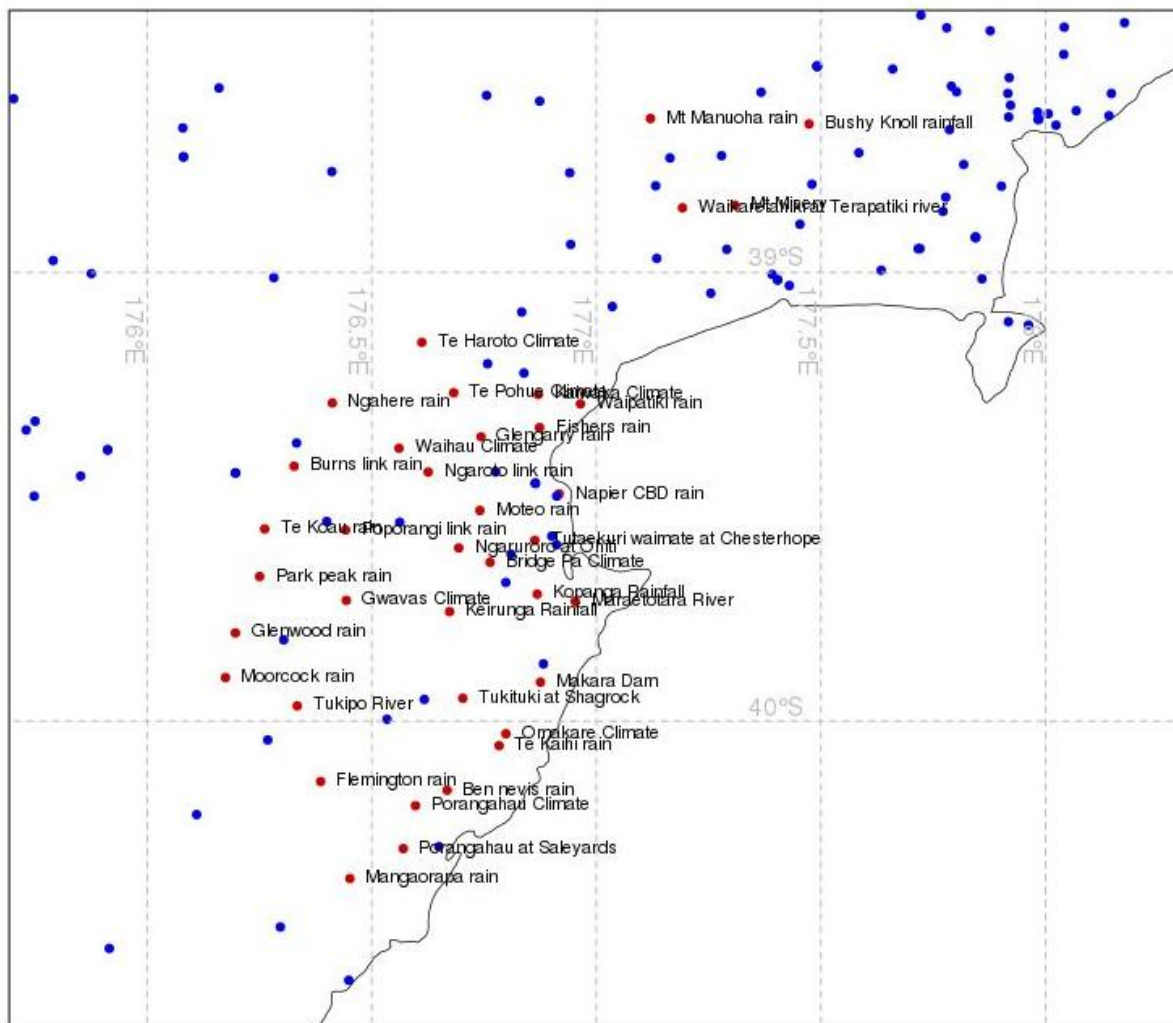


Figure 17: Gauge sites with telemetry interruptions during the passage of ETC Gabrielle (red).

An anticipated benefit of a gridded QPE product is resilience to some level of rain gauge network unavailability. The infrastructure failure experienced during Gabrielle was extreme, but it is difficult to rule out for future events. Therefore, the impact of the loss of the same rain gauge sites from the QPE workflow was investigated for both the radar and VCSN products by selectively withholding those gauges from the product generation. Exemplar accumulation plots for the data

denial QPE products for the period covering the maximum impacts are provided in
 Total Accumulation 24 hours ending 2023/02/13 16:00 (UTC)

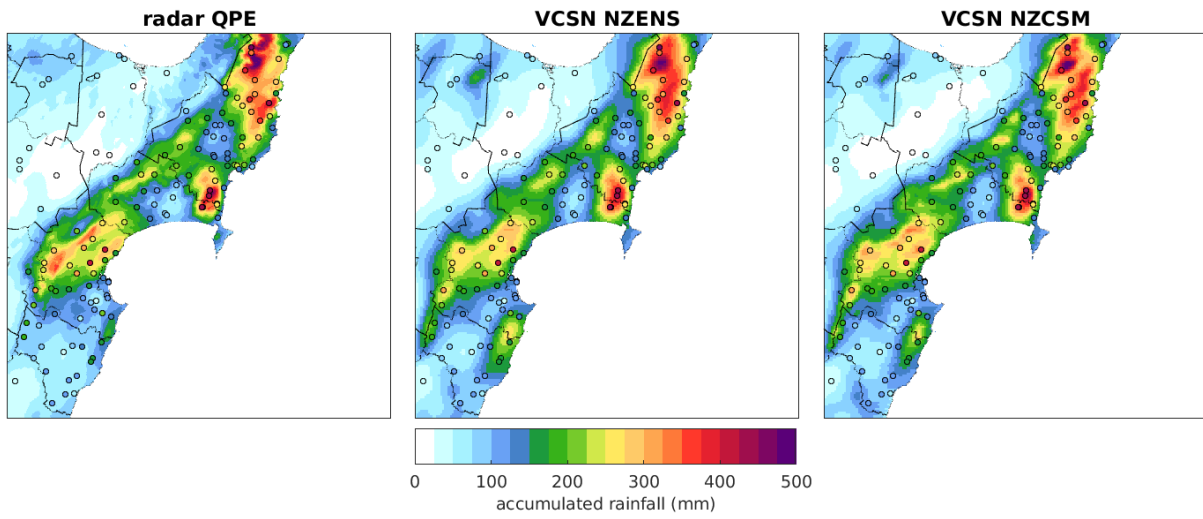


Figure 18, while

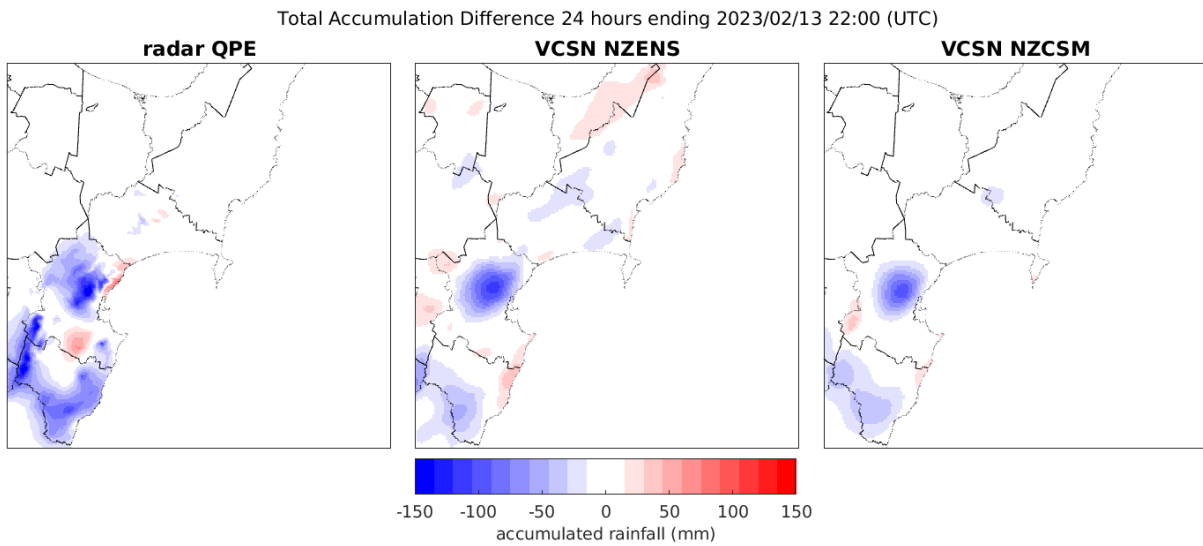


Figure 19 provides the relative change compared to a fully operational QPE system for the same time periods (as visualised in Figure 9).

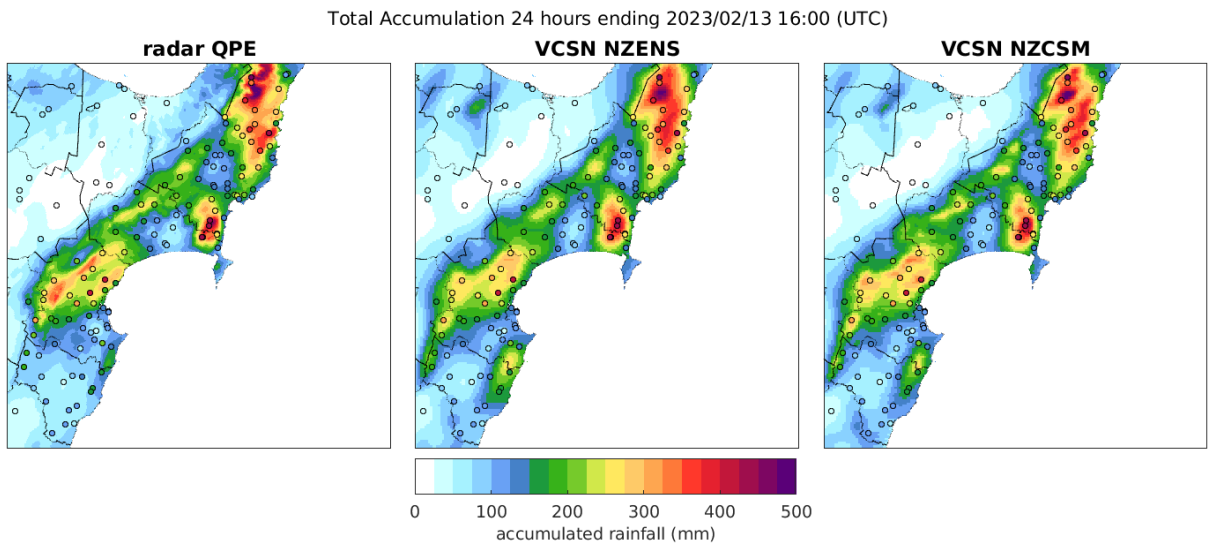


Figure 18: An example of 24-hour rainfall maps for the merged radar/gauge (left) and merged NWP/gauge (middle and right plots) analyses with the rain gauges for which telemetry failed during the event withhold from product generation.

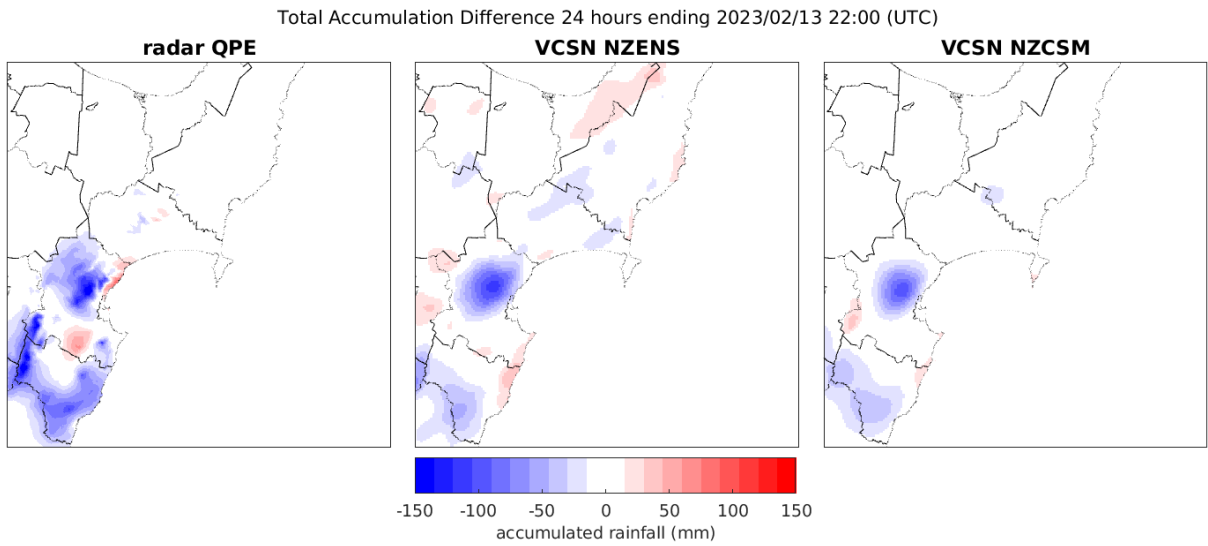


Figure 19: Difference between the data denial experiment QPE products (Total Accumulation 24 hours ending 2023/02/13 16:00 (UTC))

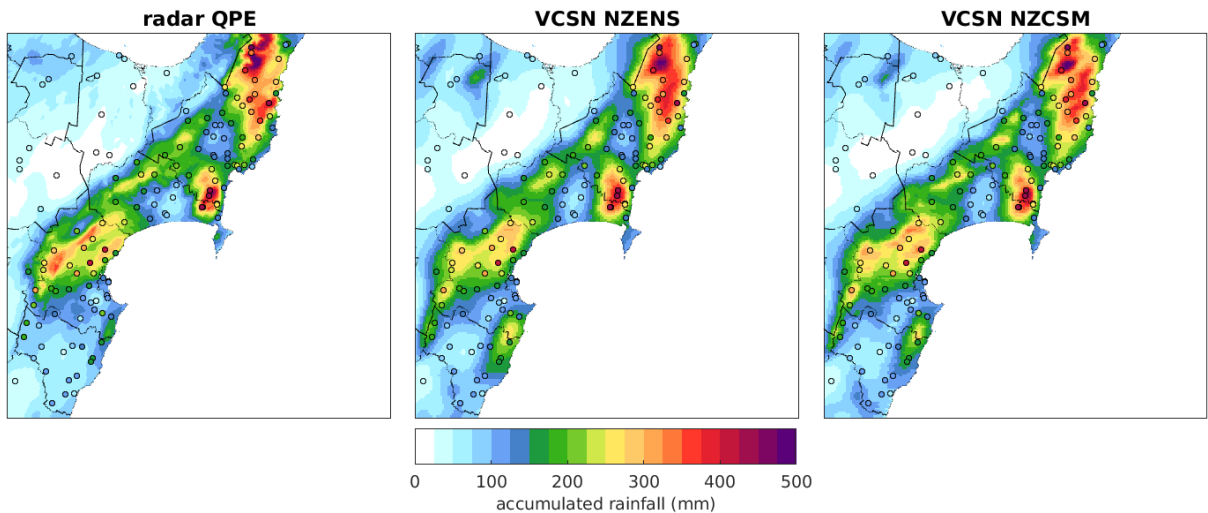


Figure 18) and QPE exemplar product based on the complete rain gauge data set (Figure 9).

5 Summary and Recommendations

This project reports on outputs of a proof-of-concept project porting the Auckland Council radar QPE system to the Hawke's Bay region for ETC Gabrielle and compares resulting QPE outputs with the VCSN system employing NWP output as the covariant field.

Both methods were successfully implemented and are free of obvious bulk errors and therefore represent immediately realisable operational QPE systems.

The QPE approaches differ in the use of either radar or NWP data to extract background spatial patterns but rely on identical rain gauge information. Statistical comparison of the radar and NWP driven QPE systems identified that the VCSN-NWP approach was slightly more skilful (in terms of RMSE and r^2) during the most intense part of the event, but otherwise very similar.

The time series results demonstrate all the QPE products struggled to reproduce the extreme accumulation depths observed at the Glengarry gauge, although inclusion of nearby gauge data moves the estimates closer to the gauge results (e.g. Figure 12).

Observation methods are generally expected to outperform NWP based approaches for QPE because while NWP contains useful information about large scale atmospheric processes, small scale stochastic variability is unpredictable and not captured well in model states. However, in this case the NWP driven analysis slightly out-performs the radar method, and this is thought to be due to the strong influence of orography on the event. Orographic forcing of moist, neutrally stable warm (onshore) flows is tied to terrain, so assuming the overall NWP conditions are correct locations of simulated rain should correspond with the topographic features, significantly decreasing NWP location errors. Meanwhile, the Mahia radar is located some 100km from the nearest orography of interest, so the beam overshoots most of the low-level processes which give rise to extreme rain accumulations in the ranges. Taken together, this event type tends to favour NWP while being particularly challenging for a distant radar station to observe. Furthermore, it is noted that the overall radar calibration has not been established, nor losses due to clutter filtering.

The impact of denial of access to data from the rain gauge network corresponding to real-world telemetry failures during the passage of ETC Gabrielle was also explored, and all QPE products were biased low in the areas impacted by the absence of rain gauge data (Figure 19). This highlights the importance of rain gauge data for any of the QPE methods and suggests that improvements in resilience to loss of the gauge network will require improved NWP forecasts or improved representation of orographic processes in the radar processing, such that the low biases around topography present in both the NWP and radar data sets are mitigated prior to introduction of gauge data. In other words, both QPE products are over-reliant on gauge data to address systematic low biases.

Nonetheless, both QPE approaches generate useable fields and in their current forms could be implemented to provide QPE capabilities in future extreme weather events, subject to the availability of rain gauge data.

5.1 Key Outcomes:

Radar QPE and VCSN-NWP based QPE systems were trialled for Gabrielle and shown to produce plausible rainfall analyses.

The radar QPE system is run operationally in other regions of New Zealand and the VCSN-NWP system requires only some technical changes to be made operational. As such, both systems could be implemented to run in real-time to support decision makers during future events.

5.2 Key Recommendations:

The investigation of the suitability of radar QPE or VCSN methods was limited by the single event type (exceptional- both in terms of rainfall depth and meteorological setup). It is likely that other types of events (e.g. convection) will be more difficult for the VCSN methods to resolved due to location errors for rainfall not being tied to topographic features and therefore randomly located within the model domain. Meanwhile, relatively unfavourable range characteristics- much of the area of interest is > 100km from the Mahia radar- suggests additional work on incorporating corrections for the variability in the vertical rain column might be required for reliable radar QPE.

6 References

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Versions

2025/04/04 Draft for Review (LSS,TCS)

2025/05/10 Comments (KK)

2025/05/28 Address comments, update with gauge comms experiment. (LSS,TCS)