

Achievement report

Improved Possible Maximum Precipitation (PMP) Estimates for New Zealand

A project conducted for the New Zealand Dam
Safety Hydrology Group

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1. Summary

This report summarises the methods underlying a new online tool that provides estimates of Possible Maximum Precipitation (PMP) in New Zealand. This tool:

1. Automates and standardises procedures currently widely used by dam safety practitioners as presented in the so-called 'Blue Book' (Tomlinson & Thompson, 1992, 1993, 1995; Campbell et al., 1994).
2. Provides an additional estimate of PMP, based on more modern data sets, underlying the large areas and long durations component of the Blue Book methodology that were not available at the time the Blue Book methodology was developed.
3. Allows for the effects of climate change to be incorporated into the PMP estimates.

The Blue Book methodology provides an estimate of PMP for catchments around New Zealand (hereafter referred to as the 'Blue Book' PMP estimate). When the same methodology is applied to more modern data sets, a different estimate of PMP is obtained (hereafter referred to as the 'minimum viable product'¹ (MVP) PMP estimate). As will be shown in the material presented below, in some regions (e.g., Northland, Gisborne, Bay of Plenty, Central North Island, Canterbury) this newer estimate is higher than would be derived using only the Blue Book, and in other regions (e.g., south-west of the North Island and the Southern Alps), lower. It is virtually certain that neither of these estimates is the true PMP. They should both be interpreted as values on some (unknown) probability density function (PDF) where several additional estimates of PMP would be required to better delineate that PDF and elucidate a 'most likely' PMP value for some prescribed catchment.

The Dam Safety Hydrology Group (DSHG), formed from 6 major dam owners in New Zealand (Meridian Energy, Mercury Energy, Contact Energy, Genesis Energy, Manawa Energy and Watercare Services), commissioned and paid for this study and associated costs.

It is important to highlight that this study generally does not:

- Modify the Blue Book methodology. It automates the methodology and applies it to the original data sets as presented in the Blue Book and to more modern data sets, but does not significantly alter the methodology itself. A large body of research has accumulated over the three decades since the publication of the Blue Book that would support the development of PMP approaches quite different to that of the Blue Book, but these are well outside of the scope of the contract that supported the work presented here. We continue to explore avenues for resourcing a larger scope of work.
- Improve the small areas and short durations component of the Blue Book methodology.

Potential for such improvements have been highlighted for future work, which include:

Automation and standardisation of the Blue Book methodology

1. Improve the automated barrier selection algorithm to account for the storm direction, width of the moisture path, and moisture paths which are not linear.

¹ While the web-app is generally referred to as a minimum viable product tool, in this report we also use MVP to differentiate the Blue Book PMP estimates from our updated estimates using more modern data sets.

Adjustment for elevation

2. Improve the adjustment for elevation (beyond a 15% reduction per 1000m barrier elevation), to reflect the latest science.

Dew point temperatures

3. Account for uncertainties in the estimates of maximum dew point temperatures, i.e., taking into account a probability-magnitude curve instead of generating a single value.
4. Improve the frequency analysis used to derive maximum dew point temperatures; specifically testing the fit of frequency distributions other than Generalised Extreme Value (GEV).
5. Use gauge data to verify the derived dew point temperature frequency analysis.
6. Confirm whether the applied relationships between surface dew point temperatures and precipitable water are valid across all New Zealand conditions.
7. Account for dew point temperatures at levels other than at 1000hPa; ideally defining an adiabat.
8. Automate the identification of moisture source region(s) for a given storm (back-trajectory analysis from the precipitation area to the moisture source region).

Moisture Maximisation

9. Investigate the suitability of the storm moisture maximisation ratio limit (currently applied as 1.8) in the context of New Zealand conditions.

Storm Catalogue

10. Reference a more complete catalogue of events (up to the present) including recent notable events such as Cyclone Gabrielle.
11. Update the storm catalogue selection process to account for C_{100} estimates.
12. Update the storm catalogue selection process to account for storm dew point temperature estimates.
13. Refine the storm precipitation reconstruction, i.e., consider alternative or higher resolution gridded data sets (e.g., Moana data or rain radar records), or use of a weather model (WRF or similar) for specific events (e.g., the May 1989 event).

Temporal Pattern

14. Create alternative or additional temporal patterns from updated storm catalogue(s) including different patterns for:
 - a) Front and back-weighted storms.
 - b) Larger and smaller area storms.
 - c) Different storm transposition regions.
 - d) A nested pattern.

Small Areas and Short Durations

15. Update the data sets used by the short duration and small areas methodology.

2. Possible Maximum Precipitation

2.1 Nomenclature

Possible Maximum Precipitation (PMP) has been referred to using several different names over the last century. Prior to 1950, the typical nomenclature was Maximum Possible Precipitation. The term Probable Maximum Precipitation was adopted by WMO (1973, WMO 1986 & WMO 2009) to ensure representation of the uncertainty surrounding any estimate of maximum precipitation. Our report uses the term Possible Maximum Precipitation, signifying a move away from components with associated probabilities, and back towards the maximum possible.

2.2 Definition

Much like its nomenclature, the definition of PMP also varies, both between and within published documents. In considering PMP to be the Possible Maximum Precipitation, we have aligned our approach to the definition presented in the introduction of WMO (2009) which includes allowances for long term climate trends:

“PMP is defined as the theoretical maximum precipitation for a given duration under modern meteorological conditions. Such a precipitation is likely to happen over a design watershed, or a storm area of a given size, at a certain time of year”.

The adopted definition is different from the definition of PMP provided in the summary of the same document which specifically excludes allowances for long-term climate trends. That definition (absent consideration of climate change) is the same as that presented in WMO (1986) which was adopted in the Blue Book.

It is important to bear in mind that established PMP methodologies are intended to represent the Possible Maximum Precipitation generated by the types of storms which have been observed. However, the methodologies do not consider types of storms which have not been observed. There will always be some underlying risk that a completely different type of storm (to the types of storms we have historically been observed) occurs, with completely different dynamics.

2.3 Probable maximum storm and probable maximum flood

The PMP estimates generated for New Zealand using the Blue Book methodology refer to a storm area of a given size at a particular location (corresponding to a design watershed). It is generally used to generate a Probable Maximum Storm (PMS) for a design watershed, from which a Probable Maximum Flood (PMF) can be derived. The PMS is one or more hypothetical storm which is equal to the PMP for durations and extents which are critical for developing the PMF for the watershed. This document focuses on the PMP. It does not detail methods to extend PMP estimates to a PMS nor a PMF.

3. Automation and standardisation of the Blue Book methodology

3.1 Summary

The Blue Book (Tomlinson & Thompson, 1992; Campbell et al., 1994) has been used routinely throughout the last 30 years to guide practitioners in the design and operation of dams in New Zealand. The Blue Book presents two different procedures to calculate PMP over:

1. Large areas (25km² to 15000km²) and long durations (12 to 72 hours).
2. Small areas (up to 1000km²) and short durations (0.5 to 6 hours).

We note that:

- Neither procedure is recommended for small areas (less than 25km²) and long durations (greater than 6 hours).
- There is limited guidance on how to estimate PMP for durations longer than 72 hours, which is likely to arise from a series of sequential storms.

In addition to the information presented in the Blue Book, several publications provide contextual and updated information which were required to automate and standardise the two procedures:

- Generation of the storm catalogue, and selection of storm transposition limits of Thompson & Tomlinson (1989) - PMP Report 1.
- Estimation of precipitable water from dew point temperatures in Thompson (1990) - PMP Report 3².
- Updates to the short duration methodology of Thompson & Tomlinson (1993).
- Summary of the long duration methodology of Thompson & Tomlinson (1995).
- International review of the PMP and PMF methodologies by the Institute of Hydrology (1997).
- McKerchar (2010) - Probable Maximum Flood: guidelines for New Zealand.
- Paine & McConchie (2012) - Auckland PMP Investigation.

PMP estimates generated using the two procedures described in the Blue Book were automated and standardised to aid quantitative comparison with the PMP estimates derived by applying the Blue Book methodology to more modern underlying data sets, and to PMP estimates from any future methodologies that may be developed. This automation was encapsulated into a 'minimum viable product' (MVP) web-based tool, available at <https://mvp.pmp.org.nz/> once access has been granted by the DSHG (contact David Payne; David.Payne@mercury.co.nz). The automation and standardisation of these procedures are discussed in the following sections.

3.2 Large areas and long durations

The Blue Book outlines a nine step procedure to compute a PMP for large areas and long durations. The steps, and how they have been automated and standardised, are detailed in the following sections.

² It is unclear whether a PMP Report 2 was ever published. Whilst it was mentioned in PMP Report 1, it is not available from either the NIWA or MetService libraries, nor from the Electricity Corporation of New Zealand library, nor from the old power libraries.

Step 1: Prescribing the catchment

The catchment for which the PMP is required can be specified by the user in two different ways:

1. The user uploads a GIS geopackage containing a polygon which defines the catchment for which the PMP should be calculated.
2. The user selects a river segment from The River Environment Classification New Zealand (Snelder et al., 2010) data set, and the catchment is automatically generated considering all upstream regions that feed that river segment³.

Step 2: Determining the 24-hour index PMP

24-hour index PMP contour maps are provided in the Blue Book (Figures 7.2 to 7.18). These were:

1. Georeferenced (using the available latitude/longitude information).
2. Digitised (by manually tracing the contours).
3. Interpolated into a single seamless high-resolution (1000m x 1000m) 24-hour index PMP map for all of New Zealand using a Kriging interpolation function.

Catchment specific 24-hour index PMP is then calculated by masking the 24-hour index PMP map (item 3 above) with the prescribed catchment.

Step 3: Adjustment for elevation

An adjustment for elevation is applied in the Blue Book to account for the effective height of any topographic barrier impeding the flow of moisture that would cause any resultant precipitation to fall outside the target catchment. Because the effective height of the barrier is taken as being the elevation 5km to 10km on the windward side of the divide, it is lower than the actual height of the barrier. The equation presented in the Blue Book to calculate this so-called barrier reduction factor is:

$$R_v = e^{-0.2 \times x} \quad (1)$$

where x is the effective barrier height in kilometres.

An algorithm was designed and implemented in the web-app to automate the calculation of the effective barrier height. The algorithm is based on a 128m resolution digital elevation model (DEM) for all of New Zealand. For each of these 128m x 128m grid cells, we extend radials along 360 compass points to the coastline. We identify the maximum altitude along each radial, with reference to the Snelder et al. (2010) data set (discussed in Step 1: Prescribing the catchment). We then calculate the effective barrier height as the average altitude 5km to 10km along the radial beyond the maximum altitude observed along that radial. For each cell in the 128m x 128m DEM this results in 360 values which show the effective barrier height in each direction. We then select the lowest of these values to provide an answer to the question 'given my current location, what is the lowest effective altitude barrier that an air parcel may have experienced along its linear journey from the ocean to my location?'. These values of x , when

³ River segments and the associated catchments are derived from 20m contour data from the NZMS260 map series (which is recommended for cartographic visualisation only).

provided to equation 1, creates an R_v field. The minimum of this R_v field is then applied to the catchment average index PMP to estimate the barrier reduction factor. A future enhancement of the tool would include visually showing the location of the selected radial and the identified location of the barrier.

The Blue Book provides limited guidance on the likely characteristics of moisture flow, which it recognises as likely to vary between storm events. It does, however, highlight that barrier heights should be related to both storm direction and local characteristics. The algorithm implemented in our web-app takes into account local characteristics (topography). If necessary, the final PMP estimate can be scaled by a different barrier reduction factor, which may be necessary for catchments where:

- a) an alternative barrier location is more appropriate and/or,
- b) the selected coastal location (moisture source) is not viable for a PMP type storm and/or,
- c) a linear moisture path is likely to be an oversimplification (e.g., a curved moisture path may be more appropriate for a cyclonic PMP type event in areas far from the coastline).

We recommend that future studies consider improved methods for generating effective barrier heights that are not only functions of the topography.

Step 4: Depth-area reduction

Table 7.2 in the Blue Book lists depth-area reduction factors for areas other than their index area of 25km² (i.e., for areas of 100km², 1000km², 2000km², 5000km², 10000km² and 50000km²), for three different regions of the country where PMP type events are typically affected by similar storms, including:

- Northern Region - tropical cyclones
- South Island-alpine Region - northwest to southeast frontal zones
- South Island-southeast Region - easterlies, slow moving depressions, or slow moving north-south frontal zones

These depth-area reduction factors are then applied to catchments of different sizes depending on the region (of the three listed above) in which the catchment is located. However, the Blue Book does not explicitly define the boundaries of each region. PMP Report 1 (Thompson and Tomlinson, 1989), a precursor to the Blue Book, presented preliminary boundaries (Figure 1), which were to be revised following storm analysis (PMP Report 2). While it is clear that the storm analysis was completed (as the results are presented in the Blue Book), it is unclear whether PMP report 2 was ever published (see footnote 2 above).

It is clear that the boundaries were altered somewhat as the Blue Book included examples of PMP calculations, of which two were eastern catchments in the South Island (Clutha and Waitaki catchments) and the South Island-alpine depth-area factor was applied for both of these catchments.

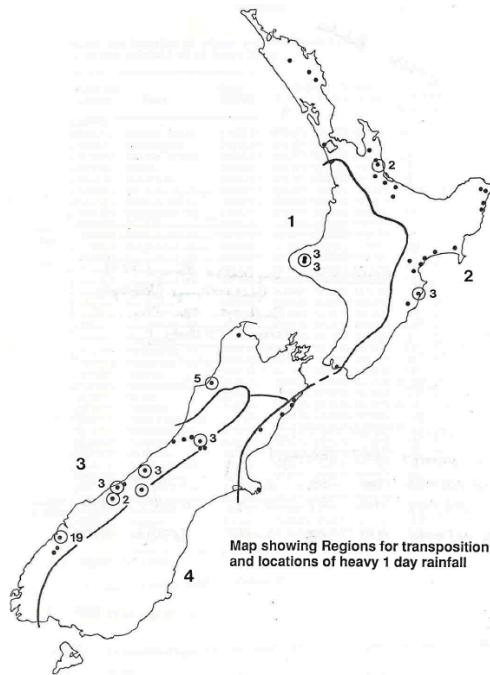


Figure 1: Transposition regions extracted from PMP Report 1 - Thompson and Tomlinson (1990)

A more recent PMF study of the Clutha catchment (Wuen et al., 2000) argued that the depth-area factor should vary spatially, in addition to the storm type specified in the Blue Book. It suggested that the South Island-alpine Region depth-area factor might also include higher altitude areas to the east of the Southern Alps, with the South Island-southeast Region limited to lower altitude areas. While it was decided to apply a weighted average depth-area parameter for the catchment (based on the proportion of the catchment at higher and lower altitudes), they did not specify a specific criterion for differentiating between higher and lower altitude areas.

We have defined the three regions as:

1. Northern - Regions 1 and 2 in Figure 1, and most offshore islands.
2. South Island-alpine - Region 3 in Figure 1, and areas within Region 4 which are more than 600m above New Zealand Vertical Datum (NZVD, 2016).
3. South Island-southeast - the portion of Region 4 in Figure 1 which is below 600m altitude and offshore islands which are south of the South Island.

Where a catchment spans two regions, an area weighted average is used to define the area-reduction factor. In these situations, a warning message is generated by the web-app to highlight that *'the catchment crosses two regions and an area weighted average has been adopted'*.

The catchment area, and the portion of the catchment within each region, are calculated by overlaying the catchment(s) from step 1 onto the map shown in Figure 1. A symmetrical sigmoidal function has been fitted to the data from Table 7.2 in the Blue Book (R^2 value above 0.94), and this function (see Figures 2a and 2b) is then used to relate the catchment area to a depth-area reduction factor. Where the catchment area is outside the range presented in Table

7.2 in the Blue Book (less than 25km^2 or greater than 15000km^2), a warning message is generated by the web-app: *'the catchment area is outside the assessed range of the depth-area reduction factor'*.

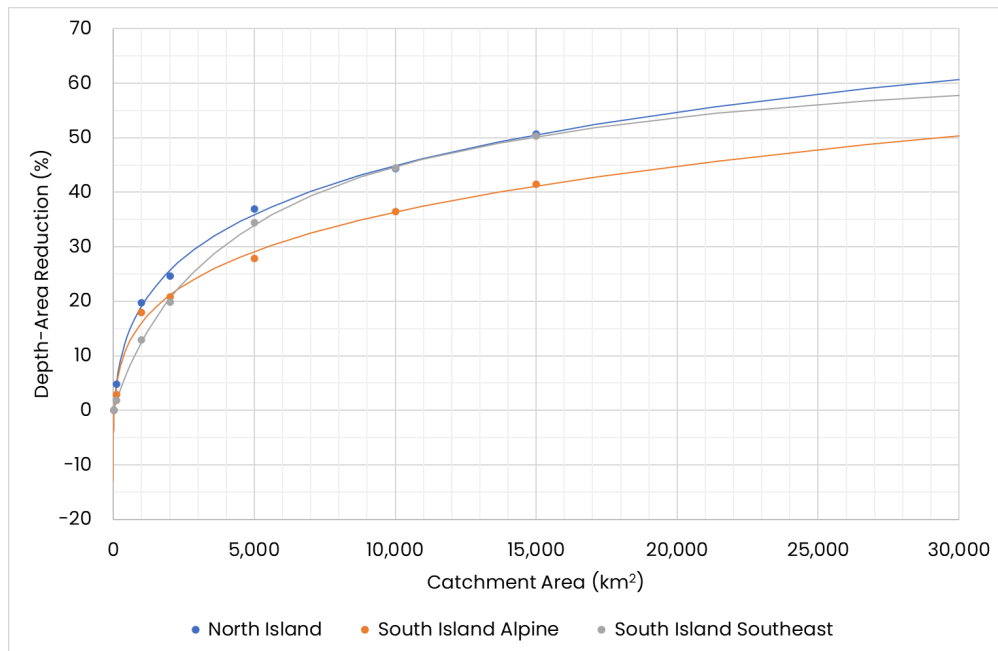


Figure 2a: Depth-area reduction factors - linear scale

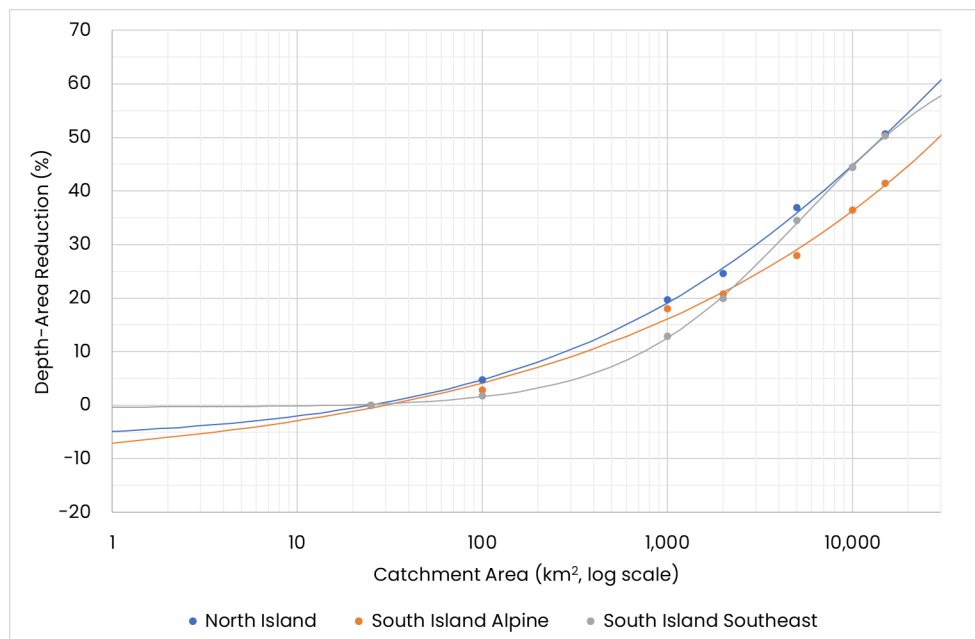


Figure 2b: Depth-area reduction factors - log scale

Step 5: Computation of average 24-hour PMP for the catchment

The barrier adjustment (Step 3) and the depth-area reduction (Step 4) factors are then multiplied by the catchment average 24-hour index PMP (Step 2), to calculate the 24-hour PMP for the catchment.

Step 6: 12/24-hour depth-duration ratios

Maps of 12/24-hour depth-duration ratios are provided in Figure 7.19 of the Blue Book. These have been:

1. Georeferenced (using the available latitude/longitude information).
2. Digitised by manually tracing over the contours.
3. Interpolated using a Kriging interpolation function into a single seamless high-resolution (1000m x 1000m) 12/24-hour depth-duration ratio map for all of New Zealand.

Average 12/24-hour depth-duration ratios were then calculated by overlaying the selected catchment extent on the 12/24-hour depth-duration ratio map.

Step 7: Depth-duration adjustments

Depth-duration adjustments based on the 12/24-hour depth-duration ratios are provided in Figure 7.20 and Table 7.3 of the Blue Book. Adjustments are presented for 12/24-hour depth-duration ratios of 0.6 to 0.9 (in 0.05 increments), and for durations between 12 and 96 hours (in 12 hour increments).

Linear interpolation has been used between the data presented in Table 7.3 of the Blue book for intermediate durations. Several curves have been extrapolated by eye to 96-hour duration. The resulting curves are overplotted onto the curves presented in Figure 7.20 of the Blue Book in Figure 3. Linear interpolation is used to define a depth-duration curve for 12/24-hour depth-duration ratios between the 0.05 increments.

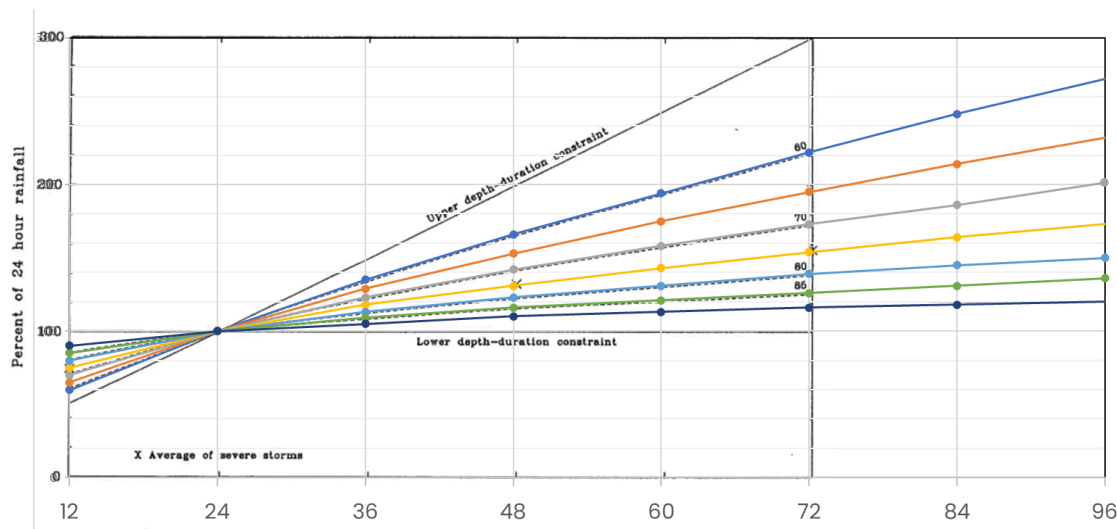


Figure 3: Depth-duration curves expressed as a percentage of the 24-hour precipitation

Step 8: Computation of catchment PMP for a range of durations

The resulting percentage adjustments from the associated depth-duration curves (from Step 7) are then multiplied by the catchment average 24-hour PMP estimate (Step 5) to produce PMP estimates for a range of durations.

Step 9: Temporal pattern

Temporal patterns, which are applicable for PMP between 12-hour and 96-hour durations, are presented in Table 7.4 of the Blue Book (reproduced in Table 1), and are differentiated for the North and South Islands. Patterns for 84-hour and 96-hour duration are assumed to be identical to that for 72 hours. For a given catchment and storm duration, the web-based tool does not reproduce the relevant temporal pattern. Instead, the user can refer to Table 1, taking into account the island on which the given catchment is located.

Table 1: Temporal Pattern - Blue Book.

Island	Duration (Hours)	Accumulation during the storm (%)										
		5	10	20	30	40	50	60	70	80	90	95
North	12	3.3*	6.8	14.8	24.1	35.4	48.2	64.1	77	86.8	94.8	97.5
	24	1.9	4.1	10.8	19.1	29.7	43.1	61.3	75.5	86.8	94.8	97.5
	48	1.5	3.5	9.4	18	30.2	45.5	65.7	79.4	88.9	95.7	98.1
	72	0.5	1.8	7.1	15.3	27.5	46.3	68.2	82	91.2	97.2	99.1
South	12	2.2	4.6	10.8	18.5	27.4	38.3	51.2	66.6	81.8	93.1	96.9
	24	1.4	3.1	7.9	14.9	25.3	38.5	55.8	76.8	90.7	97.3	98.9
	48	0.5	1.4	4.0	8.4	15.7	27.2	46.9	76.1	92.1	98.0	99.3
	72	0.4	1.2	3.6	7.3	13.8	24.9	47.8	81.5	93.8	98.3	99.4

* Example: for a 12-hour PMP storm in a North Island catchment, 3.3% of the total precipitation occurs in the first 5% (36 minutes)

3.3 Small areas and short durations

The Blue Book outlines a seven step procedure to compute a catchment average PMP for small areas and short durations. It also outlines a four step procedure to compute the associated spatial distribution of the catchment average PMP. The steps to compute a catchment average PMP, and how they have been automated and standardised in the web-app, are detailed below.

Step 1: Catchment details

The same procedures for prescribing the catchment and calculating the associated depth-area reductions as used for the large areas and long durations method are also used in the small areas and short durations method. The average altitude of the catchment is calculated from a 128m DEM, derived from the LINZ 8m DEM (Snelder et al., 2010) which was, in turn, derived from 20m contour data from the NZMS260 map series. Because it is recommended for cartographic visualisation only, we recommend future versions of the tool consider other DEMs.

Step 2: Determine 1-hour reference PMP for the catchment

The 1-hour reference PMP for New Zealand (P) is calculated using equation 2 where A is the catchment area defined in Step 1.

$$P = 220 \times e^{-0.04 \times \sqrt{A}} \quad (2)$$

This value is then adjusted in the steps described below.

Step 3: Reduction for location of the catchment

Reduction in moisture potential contour maps are provided in Figures 9.1a and b of the Blue Book. These have been:

1. Georeferenced (using the available latitude/longitude information).
2. Digitised by manually tracing over the contours.
3. Interpolated using a Kriging interpolation into a single seamless high-resolution (1000m x 1000m) reduction in moisture potential map for all of New Zealand.

Reduction in moisture potential (F_m) is then calculated by overlaying the selected catchment extent(s) on the reduction in moisture potential map. Due to the small scale of Figures 9.1a and b in the Blue Book, the Blue Book recommends rounding F_m up to the next 20mm contour interval. We consider that our more accurate digitisation of the Blue Book's figures has removed the need for such rounding.

Step 4: Adjustment for mean catchment elevation

As outlined in the Blue Book, a reduction for mean catchment elevation (F_a) is applied if the mean catchment elevation (C_E) is above 1,500m. The reduction is five percent for every 300m increase above 1,500m:

$$F_a = \min(1.0, 1 - 0.05 \times (C_E - 1500)/300) \quad (3)$$

Step 5: Catchment averaged PMP

As outlined in the Blue Book, the 1-hour reference PMP from Step 1 is multiplied by the adjustment factors $F_m \times F_a$ from Step 3 and Step 4:

$$PMP = P \times F_m \times F_a \quad (4)$$

At this point, two different methods can be used: one that uses spatial and temporal patterns, and one comprising Steps 6 and 7 as articulated in the Blue Book (see below). The scope of our work programme did not include automating or standardising the placement and selection of a spatial or temporal pattern for the short durations methodology; it is technically possible to implement this in the future (if preferred). Steps 6 and 7 described below were implemented:

Step 6: Depth-duration adjustments

Thompson and Tomlinson (1993) present an equation to determine a depth-duration adjustment, based on a 6/1-hour precipitation ratio. They recommend that the 6/1-hour precipitation ratio is determined from storm data (but do not specify what these storm data should be). We have selected the 6/1-hour ratio within the catchment from HIRDS at an average recurrence interval (ARI) of 250 years which is based on storm data.

Step 7: PMP estimates for range of durations

Results from Steps 5 and 6 are then multiplied to calculate PMP estimates for a range of durations.

3.4 Verification against existing PMP estimates

Existing PMP estimates for several catchments have been compared with outputs from the web-app. Where differences were identified, most were attributable to the rounding of values, or errors in reading values from the maps/figures in the Blue Book by earlier practitioners (highlighting the value of having an automated and standardised approach). The largest differences were identified for storm durations most different from the index/reference (24/1-hour) duration.

The following summarises the main identified differences:

1. Estimates of index/reference PMP are generally reduced. Considerable rounding was recommended in the Blue Book owing to the scale of the presented maps. This rounding is no longer required in the web-app. There were also a few instances where practitioners had incorrectly assumed the values of unlabelled contours from maps in the Blue Book.
2. Reduction factors for the location of the catchment generally decreased (again reducing the PMP). Again, the considerable rounding recommended in the Blue Book is no longer required in the web-app.
3. In the few catchments where barrier reduction factors were applied, they were considerably different. This was identified to be a result of either:
 - a. Effective barrier height being incorrectly applied by practitioners, either referencing;
 - i. mountaintops, or
 - ii. a smaller barrier behind the effective barrier.
 - b. The barrier algorithm selecting a non-plausible storm direction, and thus selecting a lower barrier, which is not between the catchment and the expected moisture source (but erring on the side of being more conservative).
 - c. The barrier algorithm not accounting for the width of the moisture inflow, and thus selecting a lower barrier, which is the lowest section of a larger higher barrier.
4. The adjustment for elevation (short duration method) was generally similar in the few cases where it was applied.
5. Practitioners had generally selected depth-duration adjustments in coarse increments. The selected 6/1-hour and 12/24-hour ratios (as generated by the web-app) were within 5% for all studies considered (i.e., the resolution of the table in the Blue Book). Regardless, the small differences had notable effects for storm durations further from the index/reference duration.

4. Updating data sets underlying the Blue Book methodology

4.1 Introduction

Data sets underlying the large areas and long duration methodology from the Blue Book have been improved, including both:

- Periodic improvements, whereby additional data (in the same form as used in the Blue Book methodology) have been added.
- Differential improvements, where new sources of data (in a form not used in the Blue Book methodology) have been added.

It is important to note that while the use of more modern data sets in the calculation of PMP for large area and long duration storms in New Zealand is a significant step forward, it largely leaves the Blue Book methodology unchanged and does little to address small area and short duration storms. There have been significant developments in the application of generalised PMP estimates internationally, and the application of new and updated methodologies presents potential for additional improvements in the estimation of PMP in New Zealand.

4.2 Framework for this and future work

Every catchment in New Zealand has a true PMP given particular climatic conditions. We are unlikely to ever know that true value. All derived PMP values are therefore only estimates. Ideally, given several estimates (each with an associated uncertainty, σ), we would be able to calculate a 'best estimate' and its uncertainty as follows:

$$\sigma_r^2 = \sigma_i^2 + (x_i - \bar{x})^2 \quad (5)$$

where:

σ_r is a revised uncertainty on the estimate of the PMP value to account for its deviation from the ensemble mean.

σ_i is the uncertainty on the estimate of the PMP value.

x_i is the estimate of the PMP value.

$\bar{x}$ is the weighted mean of the PMP estimates calculated as follows:

$$\bar{x} = \frac{\sum_{i=1}^N w_i x_i}{\sum_{i=1}^N w_i} \text{ where } w_i = \frac{1}{\sigma_i^2} \quad (6)$$

The 'best estimate' of the true PMP value (but note that this is still an estimate) would then be:

$$\overline{PMP} = \frac{\sum_{i=1}^N w_r x_i}{\sum_{i=1}^N w_r} \text{ where } w_r = \frac{1}{\sigma_r^2} \quad (7)$$

and the associated uncertainty on that mean would be:

$$\sigma_{\overline{PMP}} = \sqrt{\frac{\sum_{i=1}^N \sigma_r^2 w_i}{(N-1) \times \sum_{i=1}^N w_i}} \quad (8)$$

Strict application of the Blue Book methodology generates one estimate of PMP, while the application of the Blue Book methodology to more recent data sets generates a second estimate of PMP. Neither have associated uncertainties. Future work therefore needs to focus on

developing and applying a variety of equally scientifically valid methodologies and data sets to derive additional estimates of PMP and their associated uncertainties.

Once such a set of PMP estimates and their uncertainties has been compiled, the framework detailed above can then be used to derive a single ‘best estimate’ of the true PMP and its associated uncertainty. A significant piece of additional work would be required to achieve this. For now, we have the Blue Book PMP and the MVP PMP. Until such time as the framework detailed above can be implemented, how these two values are used in practice will require some expert judgement.

4.3 Index PMP

4.3.1 The index PMP equation

The Blue Book defines the index PMP as follows:

$$Index\ PMP = C_{100} \times MR \times \left(\frac{T_{100}}{C_{100}} - m^2 \times \left(\frac{T_{100}}{C_{100}} - 1 \right) \right) \quad (9)$$

With some algebraic manipulation, this can also be written as:

$$Index\ PMP = MR \times (T_{100} - m^2 \times (T_{100} - C_{100})) \quad (10)$$

where:

T_{100} : is the 1-in-100 year total precipitation field.

C_{100} : is the convergence only precipitation field, i.e., the precipitation occurring only as a result of convergence processes and absent of any topographically forced precipitation.

T_{100}/C_{100} : is referred to as the ‘orographic factor’.

MR : is the maximisation ratio.

m : is the storm intensification factor which modifies and reduces the orographic influence during a PMP storm.

4.3.2 Summary of data set changes from Blue Book to MVP

The key data sets underlying the derivation of the index PMP, and how they differ between the Blue Book and the MVP, are summarised in Table 2. A more detailed explanation of the derivation of the associated data sets comprising the MVP is provided in the sub-sections below.

Table 2: Key data sets used in the derivation of the index PMP and the main differences between the Blue Book implementation and the MVP implementation.

Input data set	Blue Book	MVP
100-year dew point temperatures	Gumbel fit to 20-30 years of record for 11 weather stations. Interpolated by latitude (i.e. assumed no longitudinal variance).	GEV fit to 60-year record from ERA5 ⁴ reanalysis, bias corrected against >400 weather stations. Captures latitude and longitude spatial structure.

⁴ The fifth European Centre for Medium-range Weather Forecasts (ECMWF) Reanalysis is an atmospheric reanalysis from 1940 to the present based on both assimilated weather observations and the ECMWF Integrated Forecast System - further details are provided throughout the text.

100-year total precipitation (T_{100})	Pattern in the 5-year precipitation maps from Tomlinson (1980) scaled based on 100-year estimates from a gumbel fit to daily precipitation records (in the Meteorological Service and DSIR freshwater databases, with >10 year records).	Rolling totals of total precipitation, for each target duration (see below), from CCAM model simulations spanning the pre-industrial to a climate state of 3°C of warming above pre-industrial. GEV analysis of annual block maxima. Bias corrected against 1-in-100 year HIRDS values.
100-year convergence only precipitation (C_{100})	Gumbel fit to daily precipitation records in four locations of minimal orographic effect around New Zealand (one in the North Island, and three in the South Island). Note that estimates at the location in the North Island were likely underestimated. Interpolated between these locations using the pattern in 100-year dew point temperatures (above).	T_{100} field masked over the landmass of New Zealand and offshore coastal region to exclude regions with orographic effect on precipitation. Masked region filled using 1-in-100 year gauge-corrected sea-level dew point temperature fields derived from ERA5 reanalyses.
Storm catalogue	Considered 100 events where daily precipitation records included totals greater than 300mm. All identified events were in mountainous areas. Selected 20 events based on total precipitation depth, and the area of which this covered. For those selected events, manually drew contour maps of storm precipitation and then digitised them to estimate areal extents.	Selected the 94 largest 24-hour convergence only precipitation events identified in hourly ERA5 precipitation fields (1950 to present) corrected against ~1,200 precipitation gauge records and divided by the orographic factor to derive convergence precipitation only fields. This removes the bias toward mountainous areas, and identifies storms not necessarily identified by the gauge network.
Storm dew points	12-hour persisting dew point temperature (for 24-hour duration storms) estimated to be 0.5 degrees lower than indicated by the daily dew point reading at the nearest climatological station.	Highest 12-hour average dew point (for 24-hour duration storms), averaged spatially over the precipitation area selected above, during the storm. For other storm durations, the dew point temperature window was half the storm period.
Maximisation ratio (MR)	1% exceedance value, assuming the highest maximisation ratios from the 9 largest storms in the catalogue were normally distributed.	1% exceedance value from a GEV fit considering all 94 storms in the catalogue (for each storm duration).
Storm intensification factor (m)	Unchanged	
Adjustment for elevation	Unchanged	

Depth-area reduction factors	Unchanged	
Depth-duration adjustment	Difference between the daily 100-year precipitation estimate and a 12-hour estimate derived in a similar way. Use of depth-duration curves to extrapolate to other durations. For durations greater than the index PMP, this approach has been shown to give overly conservative estimates (especially in some regions).	Repeated the index PMP calculation at all durations.
Temporal pattern	Unchanged	

As shown in Table 2, we have updated each of the input data sets making both periodic and differential changes. We have also calculated index PMP fields for durations of 1, 2, 3, 6, 12, 24, 36, 48, 72, 84, 96, 120 and 168 hours. While we have not derived uncertainties on the MVP PMP estimates, we believe that the application of the Blue Book methodology to the more modern data sets underlying the MVP results in a more scientifically defensible PMP estimate.

4.3.3 Overview of changes to index PMP

Figures 4a and 4b compare the Blue Book and MVP PMP fields.

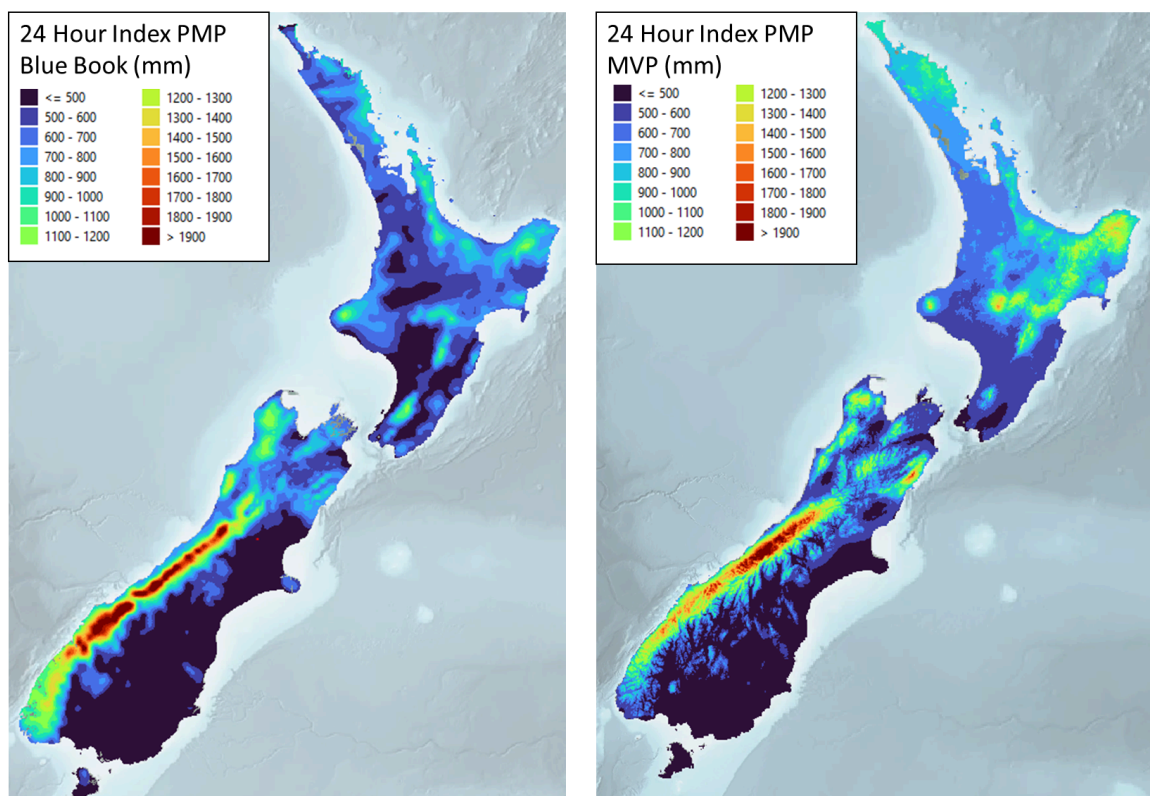


Figure 4a: (left) The Blue Book 24-hour index PMP field, and (right) the MVP 24-hour index PMP field.

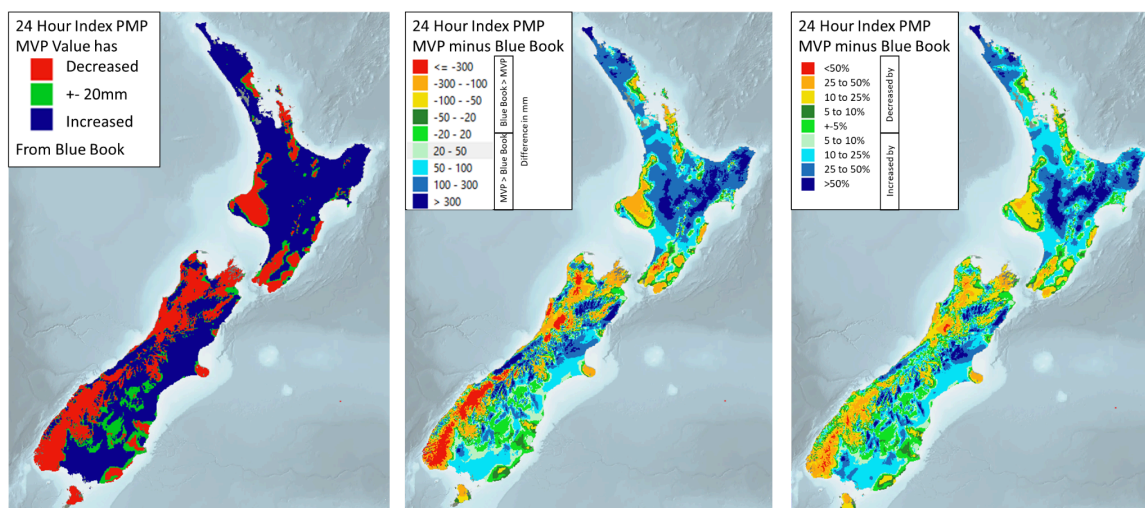


Figure 4b: Differences in 24-hour index PMP. The panel on the left shows where PMP estimates are within 20mm (green), where PMP estimates decrease in the MVP (red), and where PMP estimates increase in the MVP (blue). The centre panel shows the absolute change in mm while the rightmost panel shows the percentage change.

The MVP index PMP field has been derived at a spatial resolution significantly higher than the Blue Book index PMP field (1km x 1km cf. 10km x 10km). Figure 4b shows that in some areas estimates of the 24-hour index PMP have increased, while the estimates in other areas have decreased. Large differences are evident in areas with few precipitation gauge records (e.g., the Far North, Coromandel ranges, central North Island, Taranaki area, Taranua Ranges, Kaikoura Ranges and Southern Alps). Differences are generally smaller in areas which have high densities of precipitation gauges (e.g., the Auckland Region).

Table 3 quantifies the overall differences across each island by taking a spatial average. Over the North Island, the spatial mean MVP PMP 24-hour index estimate is 11mm higher than the Blue Book value. In the South Island, it is 14mm lower.

Table 3: Comparison of spatial mean 24-hour index PMP values from the Blue Book and MVP.

Island	Parameter	Mean	Min	Max
North	Blue Book	642	340	1134
	MVP	753	463	1608
	Difference	111	123	474
South	Blue Book	676	281	2296
	MVP	662	348	2222
	Difference	-14	67	-74

Section 4.4 and its sub-sections detail the MVP implementations made to each input required to calculate the index PMP fields for different durations.

4.3.4 Index PMP fields at durations other than 24 hours

All terms comprising the index PMP calculations (see equations 9 and 10) were computed at a range of precipitation durations.

T_{100} and C_{100}

Duration-specific T_{100} and C_{100} fields were calculated using the methods described in Sections 4.4.2 and 4.4.3 respectively. These were then used to calculate duration-specific T/C fields.

Maximisation ratios (MR)

Duration-specific maximisation ratios were calculated using the method described in Section 4.4.11. Values extracted for each duration are plotted in panel (a) of Figure 5 and were found to be well-fitted by a function of the form:

$$MR = 0.6138 \times \ln(D) + 1.6668 \quad (11)$$

where D is the precipitation duration in hours.

Storm intensification factor (m)

Functional forms were fitted to the Blue Book storm intensification factors extracted from Table 6 (Section 4.4.12), assuming, as the Blue Book did, that values remain unchanged at precipitation durations greater than 72 hours. Values at various durations and their functional fits are shown in panel (b) of Figure 5. For the North Island, the fitted function is:

$$m = -4.9655 \times 10^{-7} \times (D - 72)^3 + 0.53 \quad \text{for } D \leq 72 \text{ and } 0.53 \text{ for } D > 72 \quad (12)$$

and, for the South Island:

$$m = 1.7079 \times 10^{-5} \times (D - 72)^2 + 0.59 \quad \text{for } D \leq 72 \text{ and } 0.59 \text{ for } D > 72 \quad (13)$$

where, in both equations 12 and 13, D is the duration in hours.

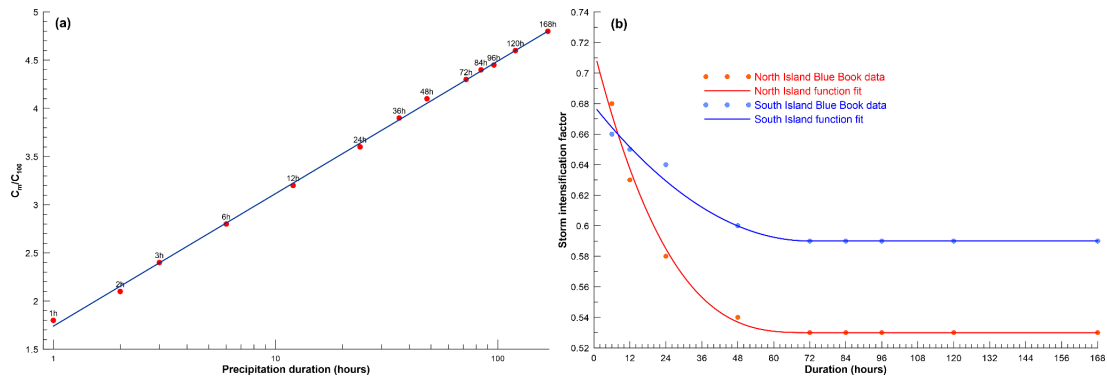


Figure 5: (a) Maximisation ratios and (b) storm intensification factors, as a function of precipitation duration.

Maps of the C_{100} field, the T_{100}/C_{100} field, and the resultant index PMP fields for seven selected durations, are shown in Figure 6. While index PMP maps have been created for a range of precipitation durations, in the sections below it is primarily the derivation of the 24-hour index PMP maps that are discussed (for direct comparison with the Blue Book), noting that the maps for non-24-hour durations are derived in exactly the same way.

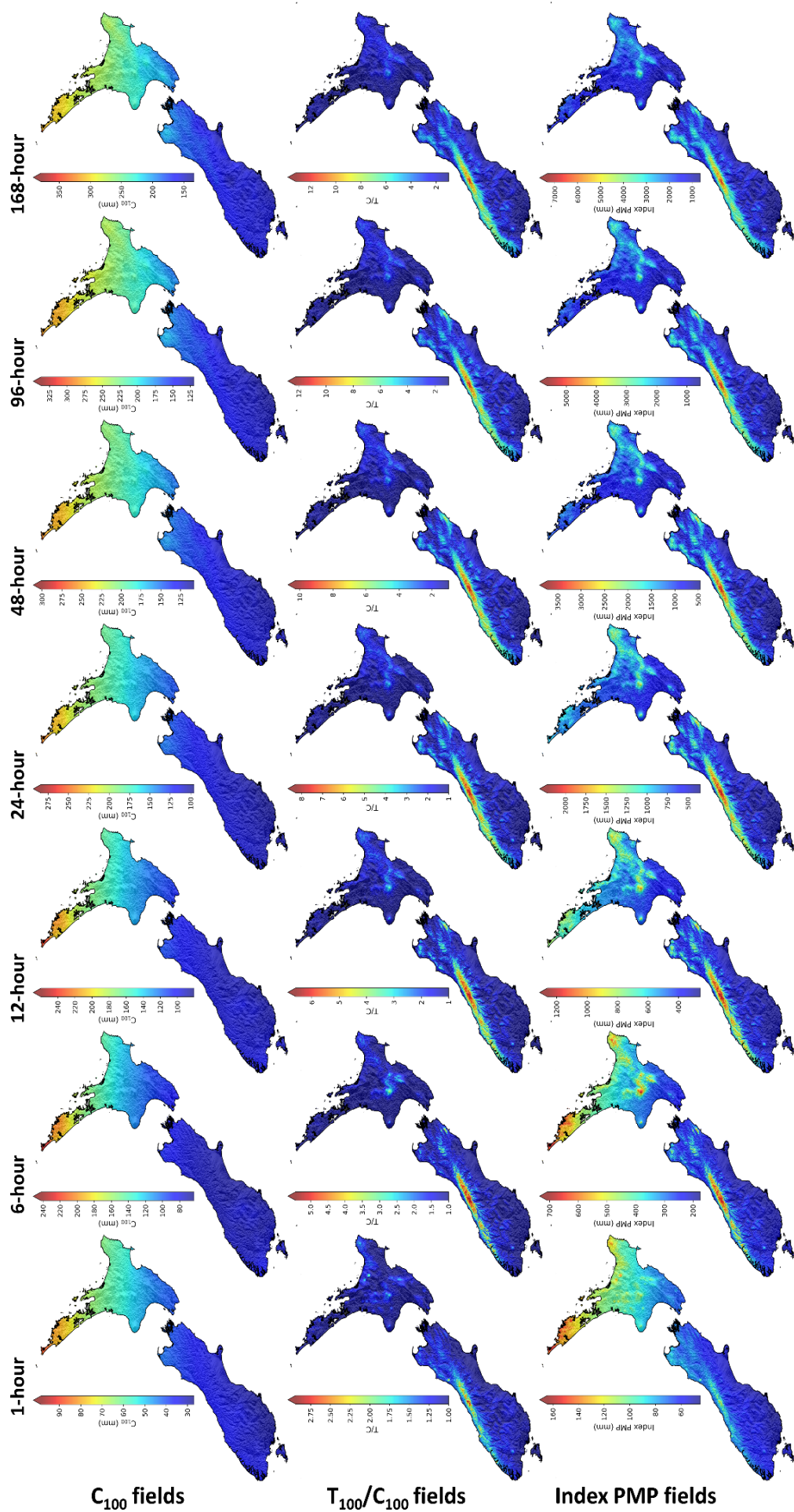


Figure 6: Example C_{100} fields (top row), T_{100}/C_{100} fields (middle row) and Index PMP fields (bottom row) for precipitation durations of 1, 6, 12, 24, 48, 96 and 168 hours.

4.3.5 Verification

As detailed in Section 4.3.3, the range of 24-hour index PMP estimates is similar to that derived in the Blue Book. The range and mean of index PMP estimates at all durations were also verified in the context of New Zealand, Australian, and world maximum measured precipitation depths (Appendix E). Generally, estimates are much lower than global records, although such values are approached in areas of the Southern Alps (at altitudes where, globally, there are very few gauges; similar values may have occurred elsewhere globally but were not recorded by gauges).

Noting that refinement of the short durations method was not within scope of the MVP, the MVP estimates of PMP for durations of 6 hours or less, may be underestimated. This is reflected in Appendix E where the MVP index PMP estimates are much lower than the world maximum gauge precipitation depths (compared to MVP index PMP estimates at durations longer than 6 hours). In saying that, McKerchar & Ibbitt (2009) identified a 1981 storm in the Kerikeri region which, when maximised, generated a 6-hour total precipitation of 528mm. This total was approximately 25% higher than the 6-hour PMP estimate from the Blue Book (420mm), implying that Blue Book PMP estimates in the area may have been too low. However, the total does not exceed the MVP 6-hour PMP estimate for the same area (~600mm), implying that the MVP 6-hour PMP estimate may be more appropriate in that area.

4.4 Description of improved data sets used to calculate MVP PMP estimates

4.4.1 Maximum dew point temperature estimates

Blue Book

The Blue Book used 6-hourly dew point temperature records from 11 weather stations to estimate a maximum 12-hour persisting dew point temperature field for New Zealand. The persisting dew point temperature is the lowest dew point temperature in the period. The stations included 9 mainland sites (records from 1960 to 1988) and 2 offshore island sites (records from 1970 to 1988). As available records were limited to 19 to 29 years, records were considered unlikely to give maximum moisture values. A frequency analysis was therefore undertaken by fitting a GEV (EV1) distribution, using the method of probability weighted moments, to monthly dew point temperature maxima for individual months at each gauge location. Maxima were screened to ensure that they were related to heavy precipitation.

From the frequency analysis, 12-hour persisting dew point temperatures with an average recurrence interval (ARI) of 100 years were estimated for each month at each gauge location. These values were assumed to approximate the maximum values based on research undertaken in other countries (WMO, 1986 & 2009). These estimated maximum persisting dew point temperatures were always greater than the maximum recorded value by a margin of 1°C to 2°C in most months. Adjustments were made to reduce estimates to 1000hPa and equation 14 (below; derived from Figure 7) was used to derive an average monthly maximum persisting 12-hour dew point temperature for any latitude.

$$T_d(^{\circ}C) = 38.6 - 0.5 \times latitude \quad (14)$$

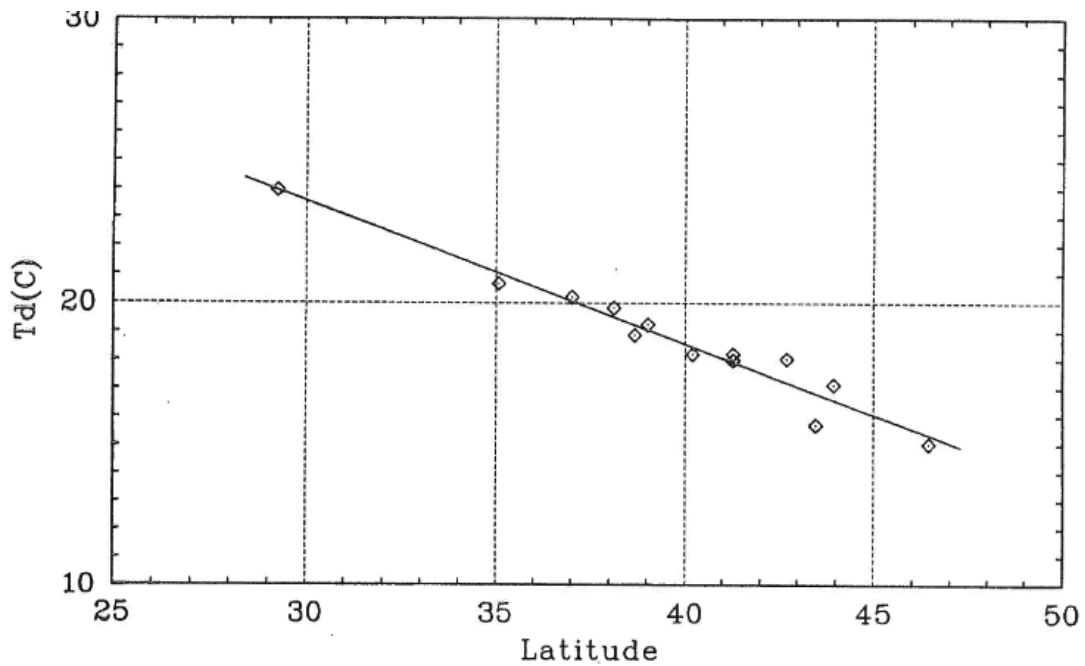


Figure 7: Average monthly maximum 12-hour persisting dew point temperature (T_d) plotted as a function of station latitude and the straight line fit used to capture this dependence.

The Blue Book split the 100-year AEP monthly maximum dew point temperatures into four seasons differentiated by large changes in estimated maximum dew point temperature. These were:

- Summer - December, January, February, March
- Autumn - April, May
- Winter - June, July, August, September
- Spring - October, November

MVP

Calculating a maximum persisting dew point temperature to characterise the dew point temperature within a storm is typical for PMP estimation and was used in the Blue Book. While effective at preventing selection of an overly high estimate, we consider that this calculation gives undue weight to a single lowest value from the highest consecutive sequence of estimates; as warned in WMO (2009): when estimating dew point temperature “*any single observation of dewpoint could be a considerably inaccurate value*”. To prevent a single low value from overly reducing estimates of storm dew point temperature, we have adopted the recommendation from Kappel et al. (2014) who suggest using the highest average dew point temperature over the storm event. The average over a sliding window spanning 50% of the index duration (i.e., 12 hours for a 24-hour event, 36 hours for a 72-hour event) was therefore selected. This is the same window as applied in the Blue Book. We note that the selected window is approximately equal to the core event duration, which was identified to vary from approximately 70% (shorter duration storms) to 50% (longer duration storms) of the storm length. Consider Figure 8 as an example: while the Blue Book uses the maximum persisting dew point temperature (orange line), the MVP uses the 12-hour average dew point temperature (grey line) selecting the maximum of those values over the storm event.

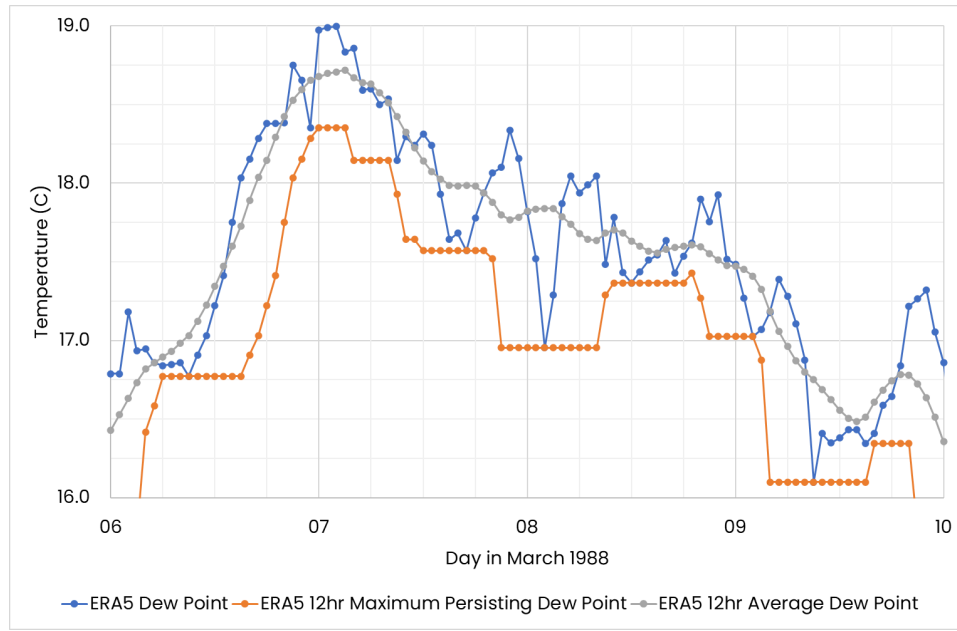


Figure 8: Three time series of different dew point temperature measures for the Cyclone Bola event in March 1988 extracted from an ERA5 cell with the storm.

To this end, a gauge-corrected sea-level dew point temperature data set was created based on hourly fields extracted from the ERA5 reanalysis (Copernicus Climate Change Service, 2024). ERA5 provides hourly estimates of dew point temperature at $0.1^\circ \times 0.1^\circ$ ($\sim 10\text{km}$) resolution over the New Zealand landmass, and at $0.25^\circ \times 0.25^\circ$ ($\sim 25\text{km}$) resolution over the surrounding ocean, from 1950 to the present. The ERA5-land surface (2m elevation) dew point temperature field at $0.1^\circ \times 0.1^\circ$ resolution is first converted to sea-level using functional fits to data from Table 2.1 of WMO (2009) to derive a temperature correction (see Figure 9).

The 0.25° field is bilinearly interpolated to 0.1° resolution (noting the long spatial scales in dew point temperature fields over the ocean which justifies such interpolation) with the values over the land being replaced by the 0.1° resolution ERA5 field reduced to sea-level. This creates a seamless 0.1° resolution field of sea-level dew point temperatures over the New Zealand landmass and ocean covering the region (48°S to 34°S and 166°E to 180°E). To facilitate gauge correction of this field, it is further interpolated to $0.05^\circ \times 0.05^\circ$ resolution (noting again the absence of topographically forced structure in this sea-level field). Differences between weather station dew point temperatures, also reduced to sea-level using the temperature offsets shown in Figure 9, and those from the $0.05^\circ \times 0.05^\circ$ resolution ERA5 field, are calculated. Differences more than 5 standard deviations away from the mean are excluded. If the resultant number of differences is less than 10, then differences from the previous hour and the following hour are also considered. The location-based differences are then modelled. First, a simple model of the form:

$$\delta = \alpha \times \text{lat} + \beta \times \text{long} + \gamma \quad (15)$$

is applied to the differences at the weather station locations. The residuals from that fit are then spatially interpolated using a Kriging method. The regression modelled difference field (equation 15) and the field of Krigged residuals are then subtracted from the high-resolution sea-level dew point temperature field to get the final field (see Figure 10).

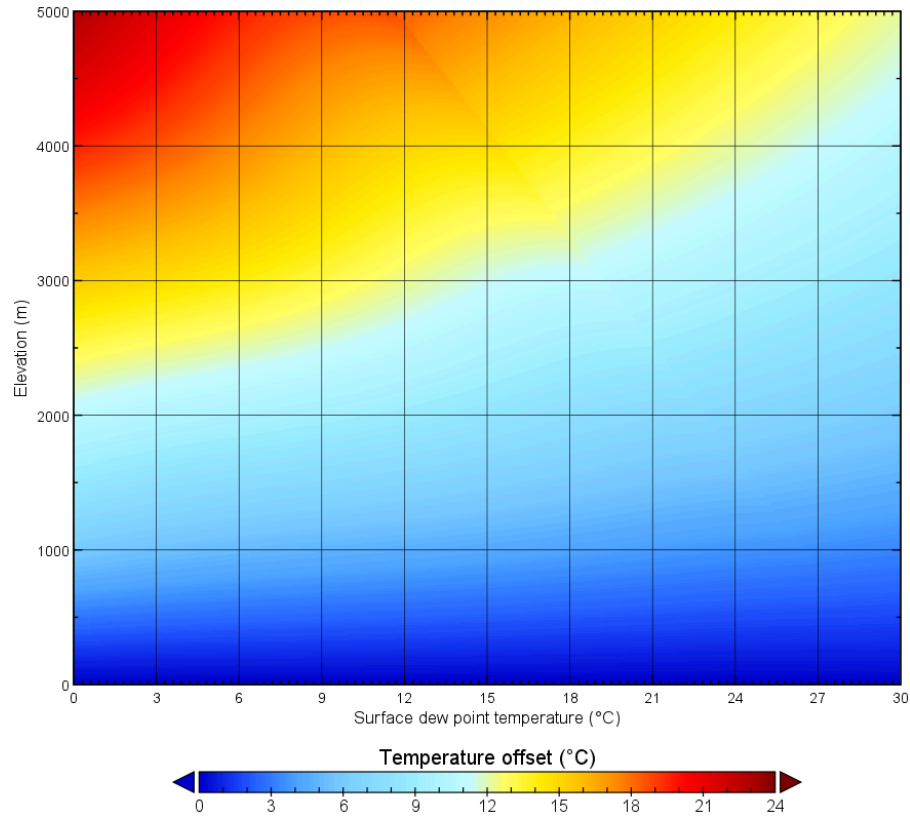


Figure 9: The corrections applied to reduce a surface dew point temperature to sea level. For example, a surface dew point temperature of 10°C at a site at 500m elevation will be inflated by 2.413°C to convert it to a sea-level dew point temperature.

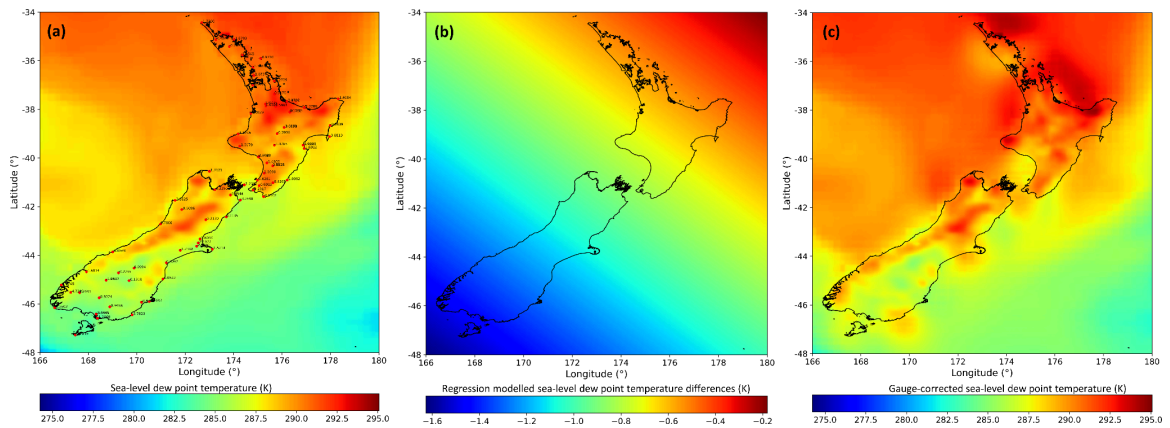


Figure 10: An example of the gauge correction of sea-level dew point temperature fields. (a) the sea-level dew point temperature generated from the ERA5 reanalysis fields for 00:00 UTC on 1 January 2000, together with the locations of the weather stations used to correct this field, and the differences between the field and the weather station data (ERA5 minus location value), (b) the regression modelled differences (in K), and (c) the final gauge-corrected sea-level dew point temperature field.

Verification of the derived gauge-corrected sea-level dew point temperature fields with reference to individual events, is discussed in Section 4.4.6 and Appendix B.

Dew point temperatures, averaged within sliding windows of width 50% of the index duration, were then calculated across the entire 70-year (1950-2019⁵) gauge-corrected sea-level dew point temperature data set. Annual and monthly maxima were extracted for each grid cell in the data set. GEV fits to these block maxima we used to calculate the associated 100-year ARI fields. As an example, both the annual and monthly block maximum 12-hour 1-in-100 year gauge-corrected sea-level dew point temperature fields are shown in Figure 11 where the monthly fields are shown as deviations from the annual field. These deviations are almost uniformly negative because the monthly block maxima will almost always be lower than the annual block maxima. These extreme values were all derived based on GEV analyses. We recommend that future studies consider applying alternative extreme value distributions and/or a regional L-moments approach.

The variation of the 1-in-100 year annual dew point temperatures with latitude from both the Blue Book (see Figure 7), and that derived from the gauge-corrected sea-level dew point temperature fields derived from ERA5, is shown in Figure 12. Note that the figure extracted from the Blue Book pertains to the *average* of the monthly 1-in-100 year 12-hour persisting dew point temperatures and not the annual *maximum* 1-in-100 year 12-hour persisting dew point temperatures, which are overplotted in Figure 12. Values from the gauge-corrected ERA5 field compare very well with those from the Blue Book when the maximum (rather than the average) of the monthly 1-in-100 year values is considered. The vertical scatter in the values extracted from the gauge-corrected ERA5 fields suggests that there may be some benefit in accounting for longitude (as well as latitude). We believe that our treatment of extreme (ARI=100 years) dew point temperature fields better characterises the moisture content of the atmosphere associated with extreme precipitation events.

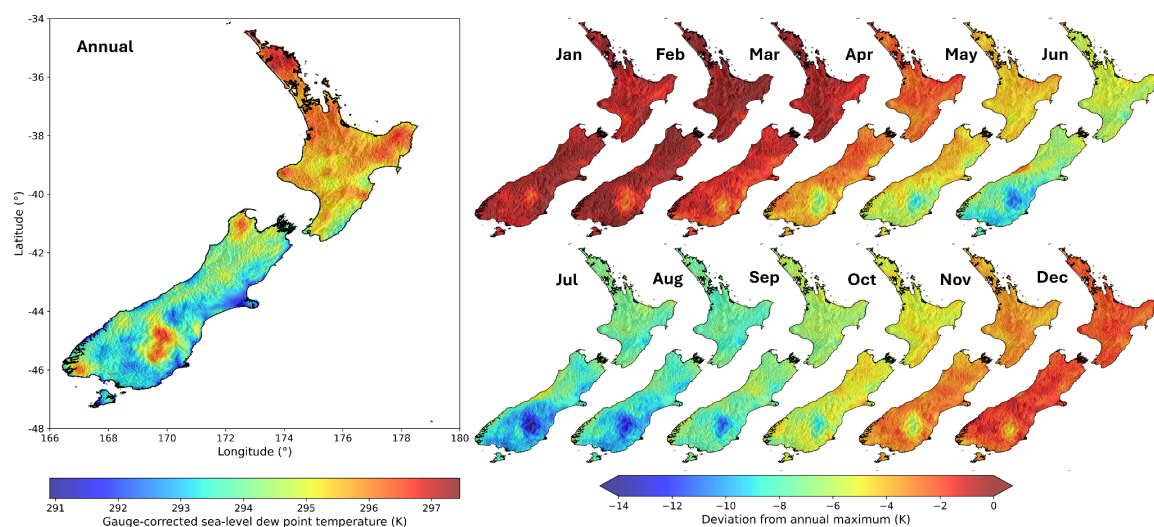


Figure 11: 1-in-100 year 12-hour average gauge-corrected sea-level dew point temperature fields, both from annual block maxima (left) and from monthly block maxima (right).

⁵ Station data beyond 2019 were not available to conduct the gauge corrections.

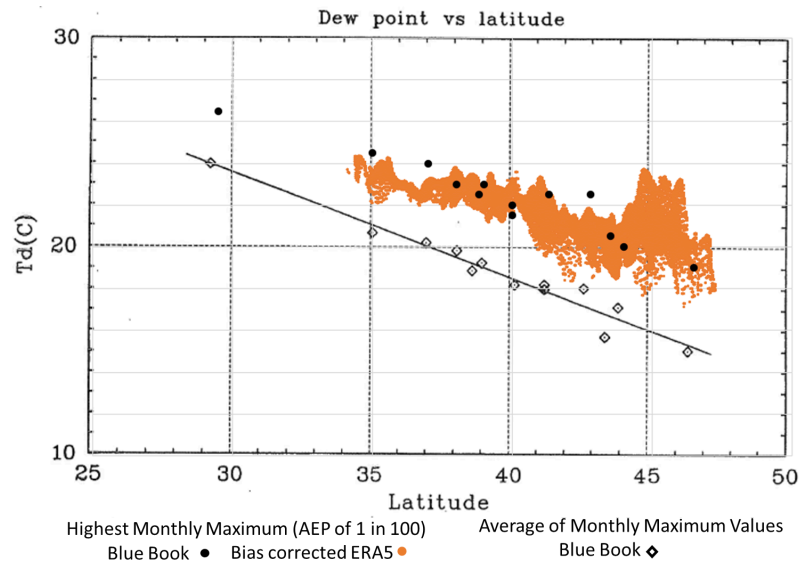


Figure 12: 1-in-100 year 12-hour persisting dew point temperature (T_d) as a function of latitude showing both values from the Blue Book and values from our gauge-corrected sea-level dew point temperature fields derived from ERA5.

Sensitivity to Selected AEP

Figure 13 shows the difference between the 1-in-100 year 12-hour average dew point temperature and the 1-in-10000 year field derived from our gauge-corrected sea-level fields. It suggests that values with an ARI of 100 years may not approximate maximum values. We recommend that the potential for dew point temperatures higher than those with an ARI of 100 years be investigated further. We note that the methodology could be extended to account for a probability-magnitude relationship (a curve, instead of a single value) associated with maximum dew point temperatures (Micovic et al., 2015).

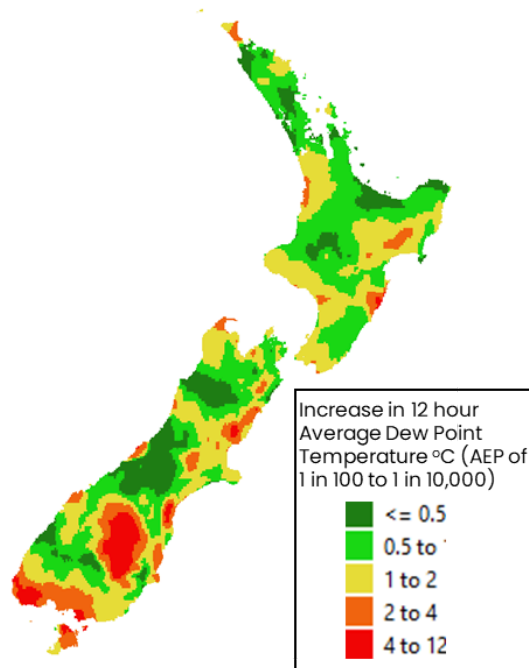


Figure 13: Difference between 1-in-100 year and 1-in-10000 year 12-hour average dew point temperature fields (10000 minus 100).

Note of Caution

The 100-year ARI gauge-corrected sea-level dew point temperature fields described above are used to represent the warmest saturation adiabat and the maximum precipitable water to be expected at the same time of year and location as the storm. WMO (2009) refers to the conclusions from two studies undertaken in the United States (Miller, 1963; United States Weather Bureau, 1960) that suggest that this is a reasonable approximation of the adiabat under saturated and pseudo-adiabatic conditions. However, Kim et al. (2020) highlight that this assumption may underestimate the adiabat (and thus the maximum precipitable water) for dew point temperatures below 18°C, at least in Japan. Interestingly, the lowest precipitable water estimates (i.e., lower surface dew point temperatures) shown in Miller (1963) and United States Weather Bureau (1960), also tended to be lower than observed. However, these were at temperatures much lower than 18°C. No study has been undertaken under New Zealand conditions to confirm whether these assumptions are valid for New Zealand. If maximum (and also storm) precipitable water were to be underestimated for dew point temperatures less than 18°C, this would affect all of the South Island storms considered in the Blue Book and a third of the North Island storms. We recommend that this is investigated in a New Zealand context in any future PMP related research. We also recommend that future studies consider accounting for dew point temperatures at levels additional to sea-level. Estimates of dew point temperatures at various levels through the atmosphere are available in data sets such as ERA5.

Verification against observations

Dew point temperature observations are taken at many meteorological stations around the country (much more than the 11 sites considered in the Blue Book). While the sea-level dew point temperature data set that we created did correct against all available station data, it may still be useful, in an extension of this work, to validate the 1-in-100 year values estimated from our data set (see Figure 11) against a similar analysis of hourly weather station observations of dew point temperature (reduced to sea-level) from gauges with records spanning at least 10 years. There are 254 such stations in the national climate database (Figure 14).

4.4.2 Total precipitation (T_{100})

Blue Book

Figures 6.14 and 6.15 of the Blue Book present contour maps of the 1-in-100 year total precipitation field (T_{100}) for the North Island and South Island respectively. The contours are at 50mm intervals in the North Island and 100mm intervals in the South Island. The *pattern* of this field was derived from a 24-hour precipitation map with an ARI of 5 years extracted from Tomlinson (1980). Findings from Chinn (1979), Griffiths and McSaveney (1983a, 1983b), Whitehouse (1985), Griffiths et al. (1989), and Horrell (1990) were used to refine the pattern in the Southern Alps and mountainous regions of the North Island. Contours were derived from a grid of points with 10km spacing. The *amplitude* of the field was then calculated from frequency analysis on precipitation gauge records from the Meteorological Service and DSIR freshwater databases following the Tomlinson (1980) methodology (i.e., EV1).

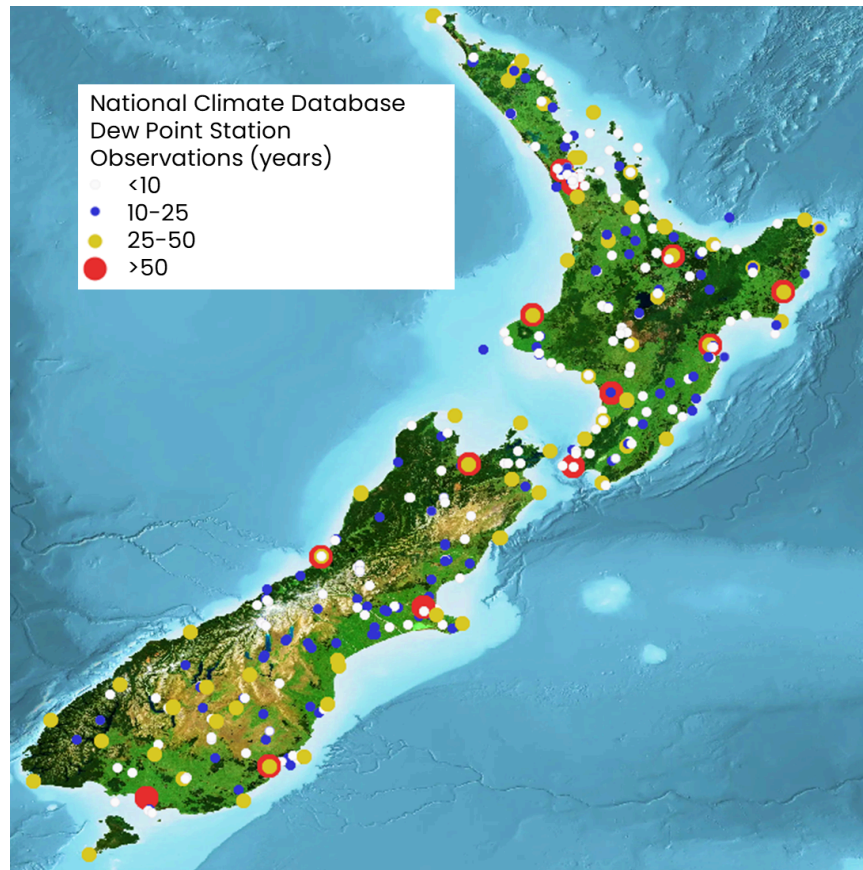


Figure 14: Weather stations with hourly dew point temperature observations available through the National Climate Database

We have georeferenced and digitised the T_{100} fields presented in the Blue Book onto a single 1km x 1km grid (using a triangulation interpolation function). During this process, it was realised that the 100mm contour interval was insufficient to capture variations in the T_{100} field over the east coast of the South Island. To this end, we additionally trialled a Kriging interpolation with reference to the spatial pattern from the HIRDS (v4, 1-in-100 year 24-hour precipitation field).

MVP

Seven data sets of 1-in-100 year total precipitation fields were assessed, each of which is described below. These included both observations-based data sets and model-based data sets, each with their advantages and disadvantages. The model-based data sets can comprise ensembles of several (or, in the case of weather@home, a few thousand) simulations spanning a much longer period than the observations-based data sets, but suffer from coarser spatial resolution and bias. Importantly for the calculation of the C_{100} field (see below), the algorithm that we developed to do this required fields that included the ocean, discounting the use of observations-based data sets. Nonetheless, we used the observations-based data sets both as comparators and to perform bias correction of the model data sets.

High Intensity Rainfall Design System (HIRDS v4)

The construction of this data set uses smoothed inverse distance weighting relationships by interpolating (with reference to elevation) between frequency analyses of precipitation gauge

data (prior to 2016/2017) from the National Climate Database and National Hydrometric Networks. This frequency analysis considered a regional L-Moments GEV fit to precipitation gauge annual maximum observations across four groups of durations. Results were derived on a 250m x 250m grid at a range of durations from 10 minutes to several weeks, but are provided at a resolution of 2km x 2km. For more details, refer to the HIRDS Technical Report (Carey-Smith, T. et al., 2018).

nn-GEV

This analysis, described in Bird (2023), considered daily precipitation data between 1960 and 2020 from 10000 sites across North America, Europe, Australia, and New Zealand. An artificial neural network was trained on these data to generate both the stationary and non-stationary (dependence on annual mean global mean surface temperature anomaly, T'_{global}) coefficients of a GEV distribution as a function of latitude and longitude over these regions. At inference, the neural network was evaluated at a spatial resolution of $0.015^\circ \times 0.015^\circ$ (approximately 1.5km x 1.5km) and at a T'_{global} of 1.2°C and 2.0°C . The nn-GEV analysis was performed on daily precipitation totals. As detailed in WMO (2009), annual maxima of precipitation derived over a 24-hour sliding window (referred to herein as 24-hour precipitation) are, on average, 13% higher than those derived from daily precipitation. As such, the nn-GEV 1-in-100 year fields should be inflated by 13% for quantitative comparison against the other fields.

Conformal Cubic Atmospheric Model (CCAM)

CCAM is a global climate model that takes as its surface boundary condition reconstructed global maps of sea surface temperatures from different sources, depending on the ensemble. The variable resolution grid employed in CCAM simulations targeted high-resolution over New Zealand (12km) and intermediate resolution over the wider South Pacific region (12–35km). For more details, refer to Gibson et al. (2023). Simulations from six CCAM ensembles were analysed:

1. A naturalised ensemble of seven simulations from 1982 to 2021 but with fixed pre-industrial atmospheric radiative conditions and with ocean surface conditions adjusted to a pre-industrial climatology estimated from observations or models.
2. An historical ensemble of seven simulations from 1959 to 2014 designed to simulate the climate history of New Zealand.
3. A single simulation from 1981 to 2020 that uses CCAM to downscale ERA5 reanalyses.
4. An ensemble of six simulations performed under the SSP126 greenhouse gas emissions scenario from 2015 to 2100.
5. An ensemble of six simulations performed under the SSP245 greenhouse gas emissions scenario from 2015 to 2100.
6. An ensemble of seven simulations performed under the SSP370 greenhouse gas emissions scenario from 2015 to 2100.

Time series of hourly precipitation from all ensembles were concatenated to create a single contiguous time series. Total precipitation in sliding windows of the requisite duration (noting that the CCAM analysis was performed for the full range of target durations) were calculated and subjected to a non-stationary GEV analysis that included the Southern Hemisphere land surface temperature anomaly (T'_{SHland}) as the climate covariate, to generate extreme precipitation fields for a range of durations and ARIs. The CCAM extreme precipitation fields generated in support of this work were evaluated at a T'_{SHland} value of 1.2°C , equivalent to a T'_{global} value of $\sim 1.0^\circ\text{C}$.

Bias corrected CCAM

This was a data set created specifically for this project. It was recognised that the CCAM model resolution of 12km x 12km was too coarse to fully capture the orographic component of precipitation over New Zealand, especially over the Southern Alps. A regression model (taking into account elevation) was developed to both bias correct CCAM against HIRDS, and increase the spatial resolution of the CCAM fields to 0.01° x 0.01°. HIRDS, being observations-based and at higher spatial resolution, is expected to provide a more realistic representation of extreme precipitation over New Zealand's landmass (but, of course, does not provide an extreme precipitation field over the ocean). This regression model bias correction was of the form:

$$(HIRDS - CCAM)_{i,j} = \alpha + \beta \times elev_{i,j} + \gamma \times CCAM_{i,j} \quad (16)$$

where $elev_{i,j}$ is the elevation at the (i,j) location. Note that the difference is partially dependent on the CCAM value itself, i.e., scales partially with the CCAM value. The modelled differences are then added to the CCAM data. At 24-hour duration, this broadscale correction reduces the sum of the squares of the differences between the CCAM field and the HIRDS field by 58% but leaves some unresolved bias between HIRDS and CCAM. To this end we conduct a quantile-quantile (Q-Q) based bias correction against HIRDS (Figure 15).

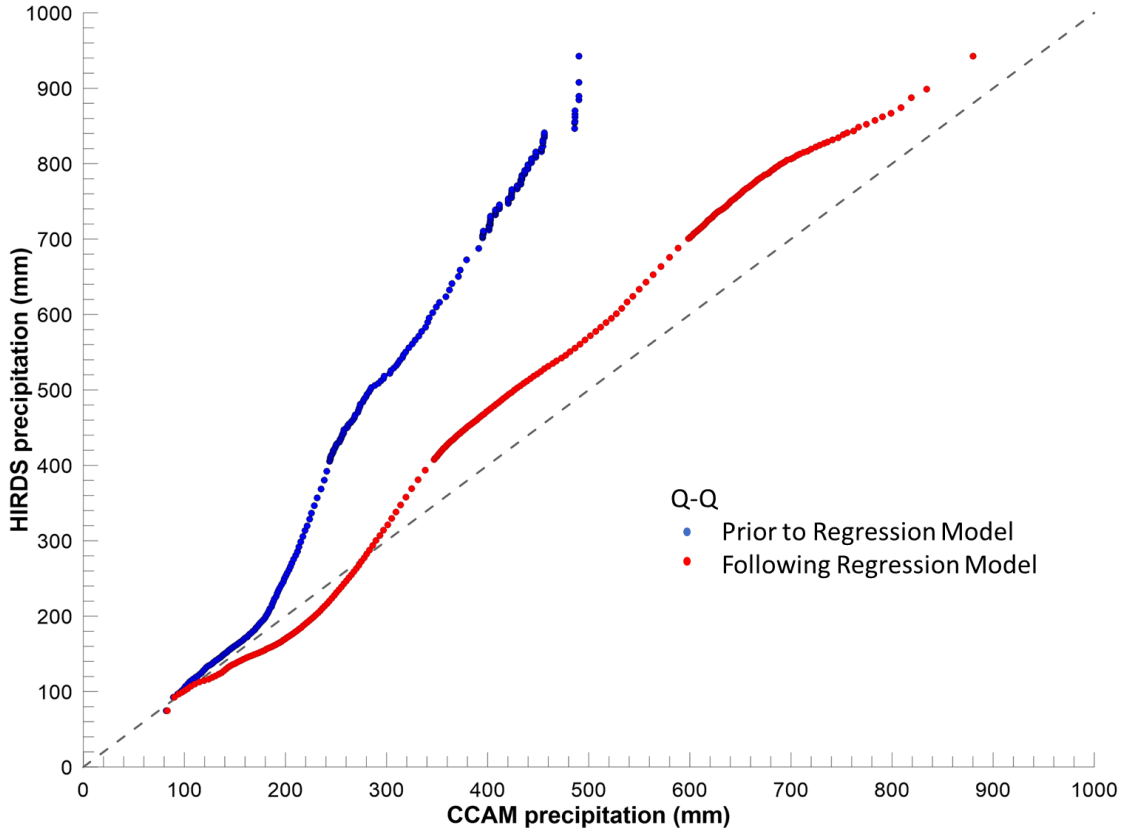


Figure 15: The bias correction of CCAM using HIRDS. The blue dots show the Q-Q correction absent the prior application of the regression-based correction, while the red dots show the Q-Q correction following application of the regression-based correction.

This two step bias correction approach was found to be necessary since while both corrections are derived only over the land (where HIRDS values are available), they need to be applied over the land and ocean. The subsequent bias correction of the CCAM extreme precipitation fields make the temperature anomaly at which they were calculated ($T'_{SHland}=1.2^{\circ}\text{C}$) irrelevant as the

temperature anomaly associated with those extremes now becomes that of HIRDS which was assumed to be at a T'_{global} of $\sim 1.0^{\circ}\text{C}$ which is what the CCAM fields were evaluated at anyway, and so there will be no inconsistency here.

weather@home

weather@home simulations are generated by nesting the high resolution HadRM3P regional model over Australia and New Zealand within a global atmospheric model (HadAM3P). For more details, refer to Black et al. (2016). The output is daily precipitation fields over New Zealand at a resolution of $\sim 0.44^{\circ}$. The simulations are driven by a sea surface temperature boundary condition, radiative forcing driven by atmospheric composition (concentrations of CO_2 , CH_4 , N_2O , O_3 , halocarbons, and sulfur species), as well as solar and volcanic forcings. The weather@home model performance was evaluated over the Australia-New Zealand region by Black et al. (2016) by comparison against the Virtual Climate Station Network for New Zealand and the Australian Gridded Climate Data for Australia, and the model was found to perform well. Simulations from eight weather@home ensembles were analysed: two ensembles (with a total of 11,014 members) that represent pre-industrial conditions, three ensembles (with a total of 8,596 members) that represent the modern day climate, and three ensembles at climate warming levels of 1.5°C (2,658 members), 2.0°C (2,643 members), and 3.0°C (2,680 members) above pre-industrial levels. As for CCAM, these data were used to calculate extreme precipitation fields for a range of ARIs, although, because the weather@home output is only at daily resolution and sliding window totals of hourly precipitation cannot be calculated, the analysis was done for daily precipitation only (the weather@home 1-in-100 year precipitation fields should therefore also be inflated by 13% for quantitative comparison against the other fields).

ERA5

Since few New Zealand surface observations (data from around 40 sites at best) are assimilated into ERA5, it is well known that this data set does not adequately represent precipitation extremes over New Zealand (it is not clear whether this is related to a specific type of precipitation mechanism, or is a more general trend). A comparison of 1-in-100 year 24-hour precipitation maps derived from ERA5 and similar maps derived from observational sources over New Zealand, indicate that ERA5 underestimates extreme precipitation and also results in different spatial patterns of extreme precipitation.

Bias corrected ERA5

Noting the underestimation of extreme precipitation in the ERA5 data set, a gauge-corrected ERA5 data set was created specifically for this project. A log Pearson Type III distribution was fitted to 14-day precipitation totals from both individual cells in the ERA5 data set and gauges with records longer than 50 years (see Figure 16) to derive an associated PDF.

The log Pearson Type III distribution was also applied to gauges with shorter than a 50-year record using the shape parameters from the nearest gauge with a greater than 50-year record. PDFs were then interpolated between gauge locations. ERA5 values in each cell, at each time step, were adjusted using the difference between the ERA5 PDF and the PDF derived from gauge records. GEV analysis of this data set was used to derive extreme precipitation fields at $0.1^{\circ} \times 0.1^{\circ}$ (approximately 10km x 10km) resolution for a range of durations from 1 hour to 1 week.

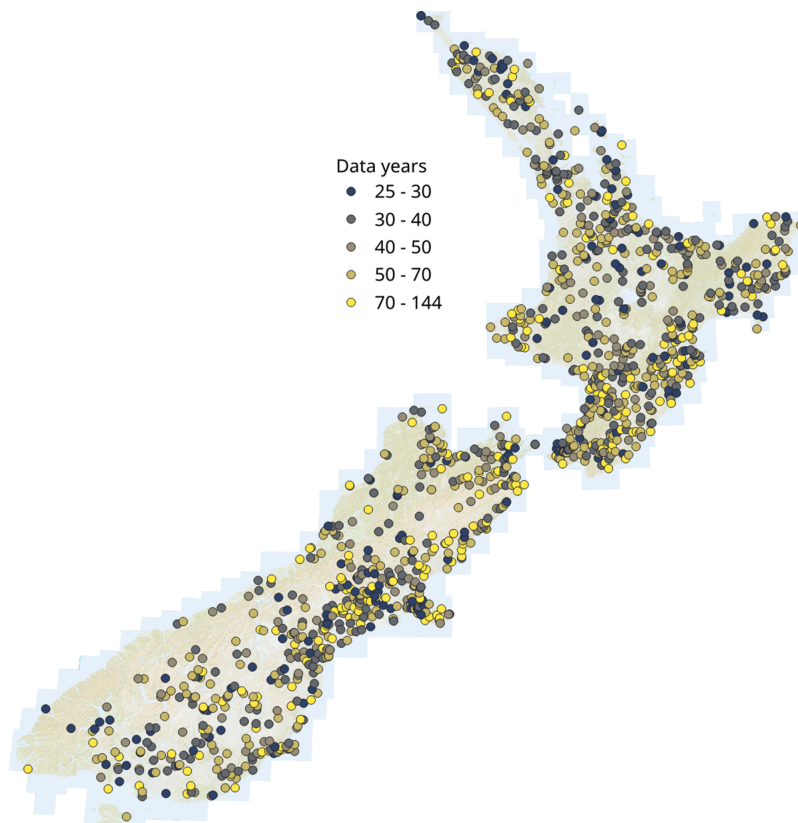


Figure 16: The locations of the precipitation gauges used to correct ERA5. These gauge data were sourced from NIWA, MetService, Regional Councils, and FENZ. There are 1,200 gauges with records of 25 years or more, and 255 gauges with records of 70 years or more.

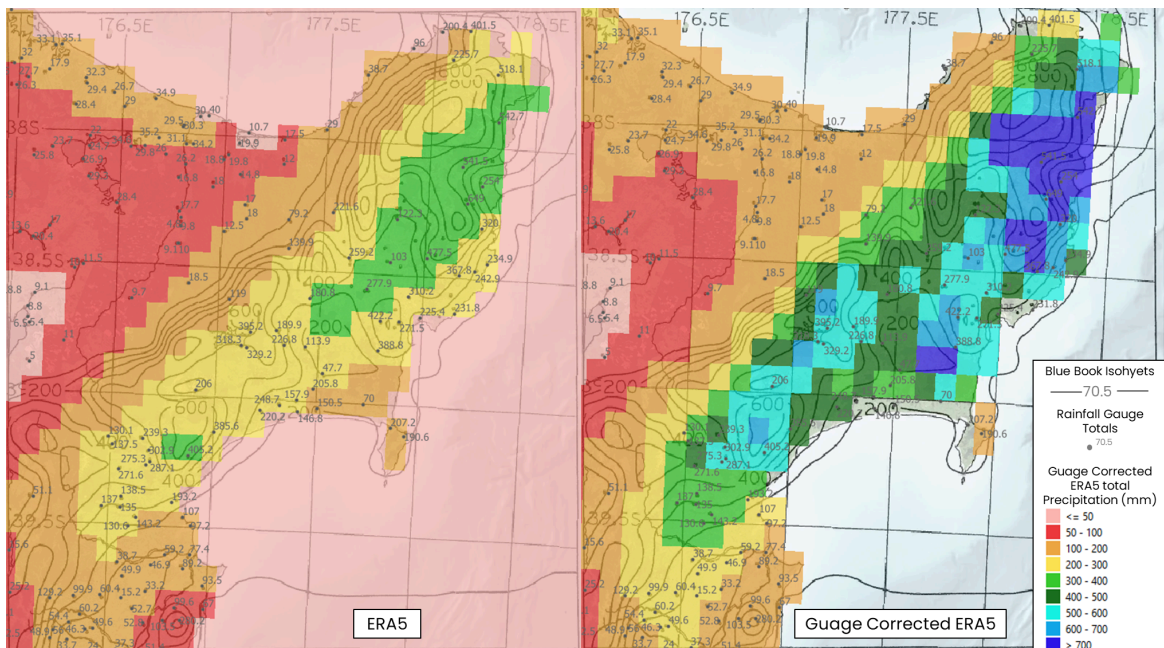


Figure 17: Comparison of total precipitation for Cyclone Bola over the 3-day period from 6 to 8 March 1988 for the East Cape: (left) the coloured cells show the raw ERA5 total precipitation field and (right) the coloured cells show the gauge-corrected ERA5 total precipitation field. Also shown in both panels is the total precipitation map presented in the Blue Book (contour lines) and the gauge locations with their associated 3-day total precipitation values extracted from the National Climate Database (where available).

The precipitation isohyets generated from the gauge-corrected ERA5 precipitation fields were evaluated in three ways:

1. Comparison with 17 of the 20 storm patterns documented in the Blue Book (see Figure 17), noting that 3 storms detailed in the Blue Book preceded the period covered by the gauge-corrected ERA5 data set. A wide range of matches for these various storms was found (see Appendix A for details).
2. Comparison with gauge observations (see also Figure 17). The gauge-corrected ERA5 fields tend to slightly overestimate gauge totals in low lying areas and underestimate some gauge totals in higher altitude areas.
3. Comparison with Blue Book convergence precipitation tables for 8 of the 20 events selected for detailed analysis in the Blue Book (see Appendix C). For most storms, the gauge-corrected ERA5 fields tended to be higher than the Blue Book estimates. This was somewhat expected given that the MVP estimates were derived directly from the area with the highest convergence precipitation during the event, whereas the Blue Book estimates were derived taking the convergence component from the area of highest total precipitation during the event.

1-in-100 year fields of 24-hour precipitation have been derived from each of the data sets described above and are compared in Figure 18 along with the digitised equivalent field from the Blue Book (their Figures 6.14 and 6.15).

The differences in these fields from that provided in the Blue Book are presented in Figure 19. It should be noted that the plotting of the T_{100} field in the Blue Book at a contour interval of 100mm presents a challenge for interpolation over the east coast of the South Island. To additionally demonstrate the magnitude of the differences between the T_{100} fields and the equivalent Blue Book field, ratios of various combinations of these fields (excluding that from the Blue Book) are shown in Figure 20.

In general, all of the T_{100} fields derived from the newer data sets compiled for the purpose of this study show differences in magnitude and spatial morphology from that found in the Blue Book, particularly in mountainous regions. A brief summary of these differences follows:

- **HIRDS (v4)** shows T_{100} values similar to, or lower than, those of the Blue Book over non-mountainous regions, with a very similar spatial pattern. When compared to the other data sets, and especially the Blue Book, there is more spatial structure in the HIRDS data set, likely as a result of the finer spatial resolution at which the HIRDS field has been derived. Interestingly, while HIRDS is expected to be uncertain and least appropriate over mountainous regions (and especially the Southern Alps), it is over these regions where it shows better agreement with the values from the Blue Book than the other data sets considered.
- **nn-GEV** (AI fields in Figure 19) shows T_{100} values similar to both the Blue Book and HIRDS across most of the North Island but lower values in the South Island and over mountainous areas.

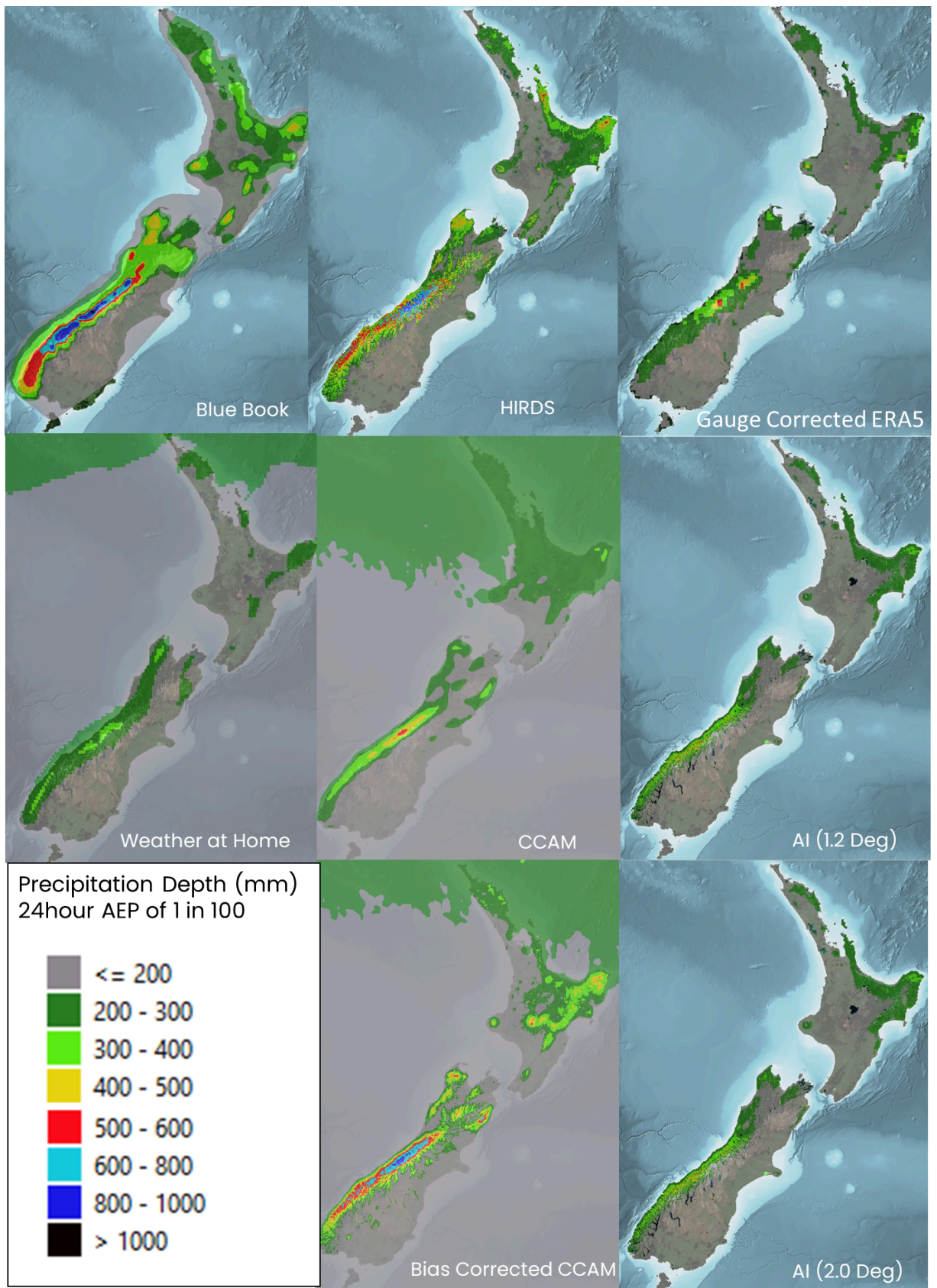


Figure 18: 24-hour 1-in-100 year total precipitation (T_{100}) estimates from the data sets compiled for use in this study and from the Blue Book (upper left). The two AI panels show results from nn-GEV T_{100} fields generated at 1.2°C and 2.0°C of warming.

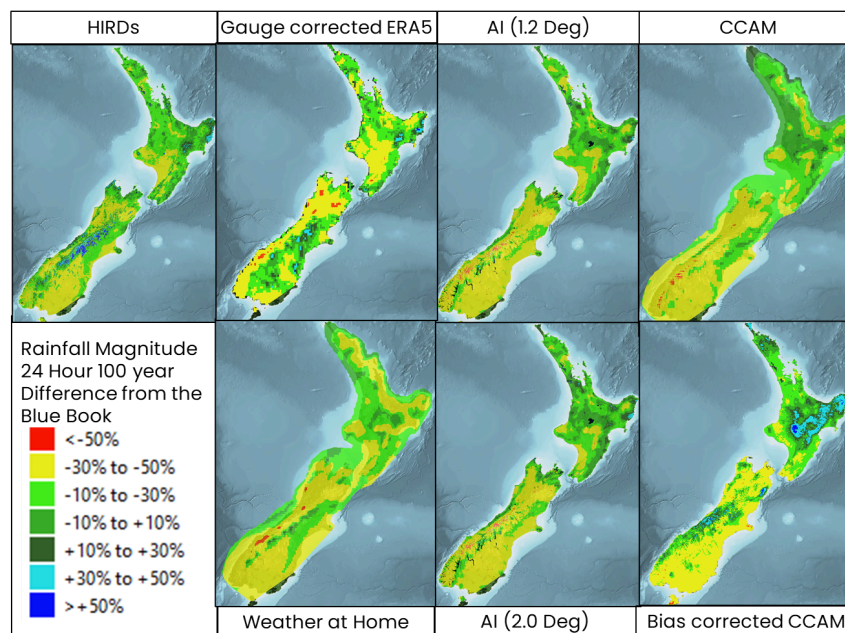


Figure 19: Differences between the 1-in-100 year 24-hour total precipitation (T_{100}) fields from the data sets compiled for this study (x) and that from the Blue Book (x minus Blue Book).

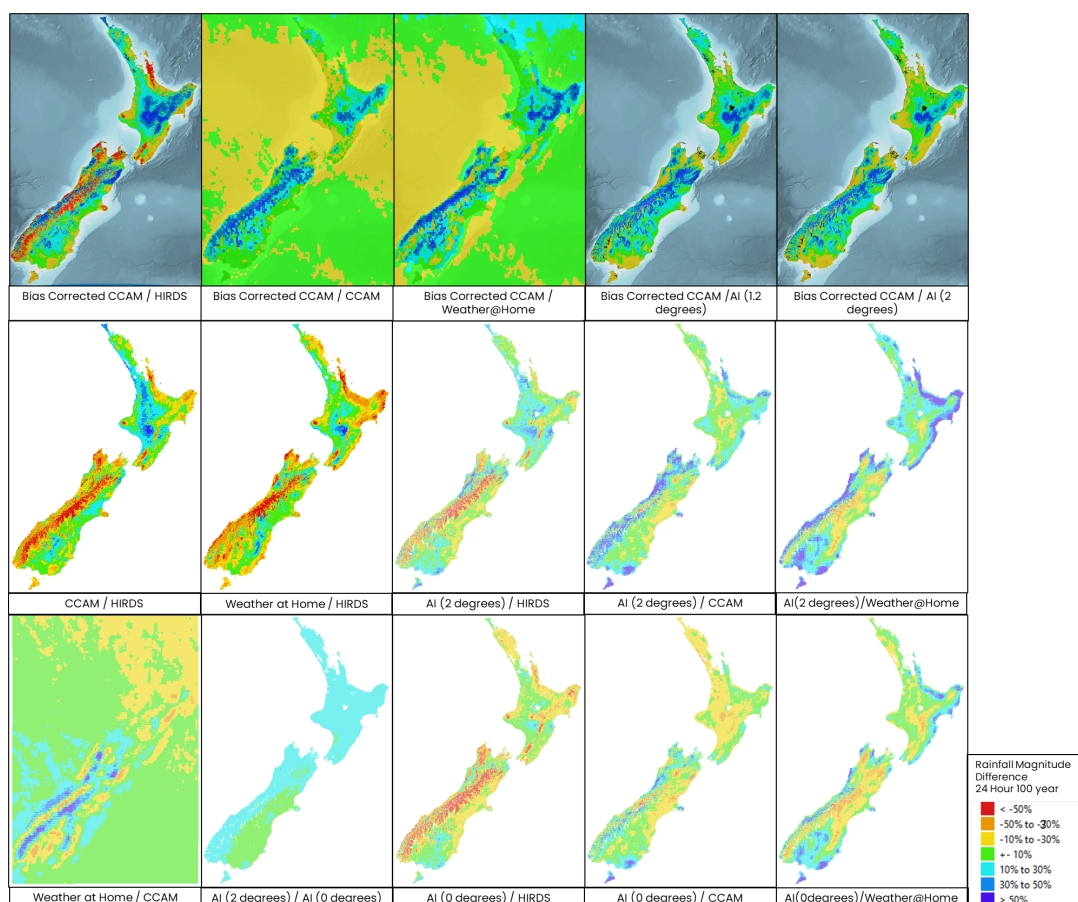


Figure 20: Ratios of 1-in-100 year 24-hour total precipitation data fields for selected combinations of data sets.

- **weather@home, CCAM and gauge-corrected ERA5.** All three of these data sets are fundamentally model output though, in the case of gauge-corrected ERA5, with significant nudging towards observed values. The data sets are generated at the underlying resolution of the model, i.e, 50km x 50km, 12km x 12km, and 10km x 10km respectively. These comparatively coarse resolutions of the underlying models result in the effects of orography on extreme precipitation being under-estimated (largely corrected for in the gauge-corrected ERA5). The gauge-corrected ERA5 T_{100} field shows values generally similar to, or slightly lower than, the Blue Book over much of the North Island and higher values in the east and lower values in the west (and other high elevation regions) over the South Island. CCAM shows values similar to the Blue Book over much of the North Island, but generally lower values over most of the South Island. The same is true of weather@home, although the weather@home differences tend to be more negative, indicating lower T_{100} values in weather@home compared to the Blue Book and CCAM.
- **Bias corrected CCAM** shows T_{100} values similar to the Blue Book over much of the North Island but with higher values over the Central Plateau and towards the East Coast, and lower values to the south-west of the North Island. Other than very high altitude regions, over the South Island the values tend to be 30 to 50% lower than those in the Blue Book, in agreement with several of the other data sets.

Several factors were considered when selecting which of these data sets to use as the T_{100} field:

1. *Spatial resolution:* All else being equal, we preferred data sets at high spatial resolution over coarse resolution data sets with the expectation that these would resolve high spatial gradients in the T_{100} field.
2. *Similarity to Blue Book:* A guiding principle for this work was to create an extension to the Blue Book by way of use of more modern data sets. As such, where possible, we preferred a T_{100} field whose spatial pattern and amplitude were similar to that of the Blue Book.
3. *Data over the ocean:* The method used to derive the C_{100} field (see below) required screening a T_{100} field over the landmass of New Zealand and nearby coastal regions, thereby omitting areas over which orographically forced precipitation could occur, and then intelligently interpolating over the screened area. This only works if data are available over the ocean. On the face of it this would prohibit all observations-based data sets. However, it would be conceivable to replace all landmass values in some modelled data set with values from an observations-based data set, bias correcting the model at its interface with the observational data. This consideration would prefer model data sets, but would conflict with consideration (1).

Within these considerations, we selected to use the bias corrected CCAM T_{100} field as the defining T_{100} field for calculating the index PMP since:

- It has been derived at 1km x 1km resolution.
- Has many similarities in structure and amplitude compared to the T_{100} field in the Blue Book.
- By bias correcting against HIRDS, which has broad community acceptance and also shows many similarities to the Blue Book T_{100} field, combines the best of both CCAM and HIRDS.

- Provides data over the land and ocean with no discontinuity between the land and ocean.
- When calculating the orographic factor (T_{100}/C_{100}) in the index PMP calculation, any amplitude biases in these fields would cancel.

Conceivably, the T_{100} from data set A (available only over the landmass of New Zealand) could have been used to provide the T_{100} field and the T_{100} field from data set B (available over land and ocean) could have been used to derive the C_{100} field. However, any biases between the two would have the potential to significantly bias the orographic factor which appears as a first order term in the calculation of the index PMP. We also considered taking the weighted average, maximum or minimum value (at a given location) from multiple data sets. However, differences in spatial resolution and availability of data over the land and ocean would have resulted in a spatially biased mean. While the bias corrected CCAM T_{100} field was used for the MVP, we note that future work should focus on deriving a more comprehensive T_{100} field that optimally combines T_{100} estimates from multiple sources.

4.4.3 Convergence Precipitation (C_{100})

Blue Book

At the time of the publication of the Blue Book, it was not possible to obtain precipitation estimates over the ocean (where orographic influence on precipitation is absent). As such, the 1-in-100 year convergence only precipitation field (C_{100}) presented in the Blue Book was derived by considering total precipitation in four regions of New Zealand where precipitation was assumed to be minimally affected by orography, i.e., primarily the (i) Aupouri Peninsula in Northland, (ii) and Coastal Canterbury between the Rangitata and Ashburton rivers, and, though probably more likely to be influenced by orography, (iii) Farewell Spit and Golden Bay, and (iv) the Foveaux Strait. To extrapolate from these four regions to the rest of the country, the pattern in maximum 12-hour persisting dew point temperatures was used (see above). With reference to expected moisture sources, a field covering all of New Zealand was generated. Further adjustments were made to that field, taking into account an equation from Haltiner and Williams (1979).

MVP

We compare the Blue Book C_{100} estimates over the four regions detailed above to the T_{100} field values (which, over these four regions of supposed minimal orographic influence, are expected to be equivalent to the C_{100} values) from a selection of the new data sets collated in support of this project (Figure 21). Over Coastal Canterbury and Foveaux Strait, a very good comparison is obtained with all five data sets. Over Farewell Spit and Golden Bay, all five data sets show very comparable estimates of the convergence only precipitation as well as good agreement with the values derived in the Blue Book (though generally higher than the Blue Book values). In contrast, over the Aupouri Peninsula, data sets other than HIRDS indicate substantially higher values than those derived in the Blue Book. The Aupouri Peninsula was the only location identified in the North Island with minimal orographic influence in the C_{100} analysis presented in the Blue Book. As such, this single value has a disproportionate effect on C_{100} values over the whole of the North Island, i.e., everywhere north of the Farewell Spit and Golden Bay.

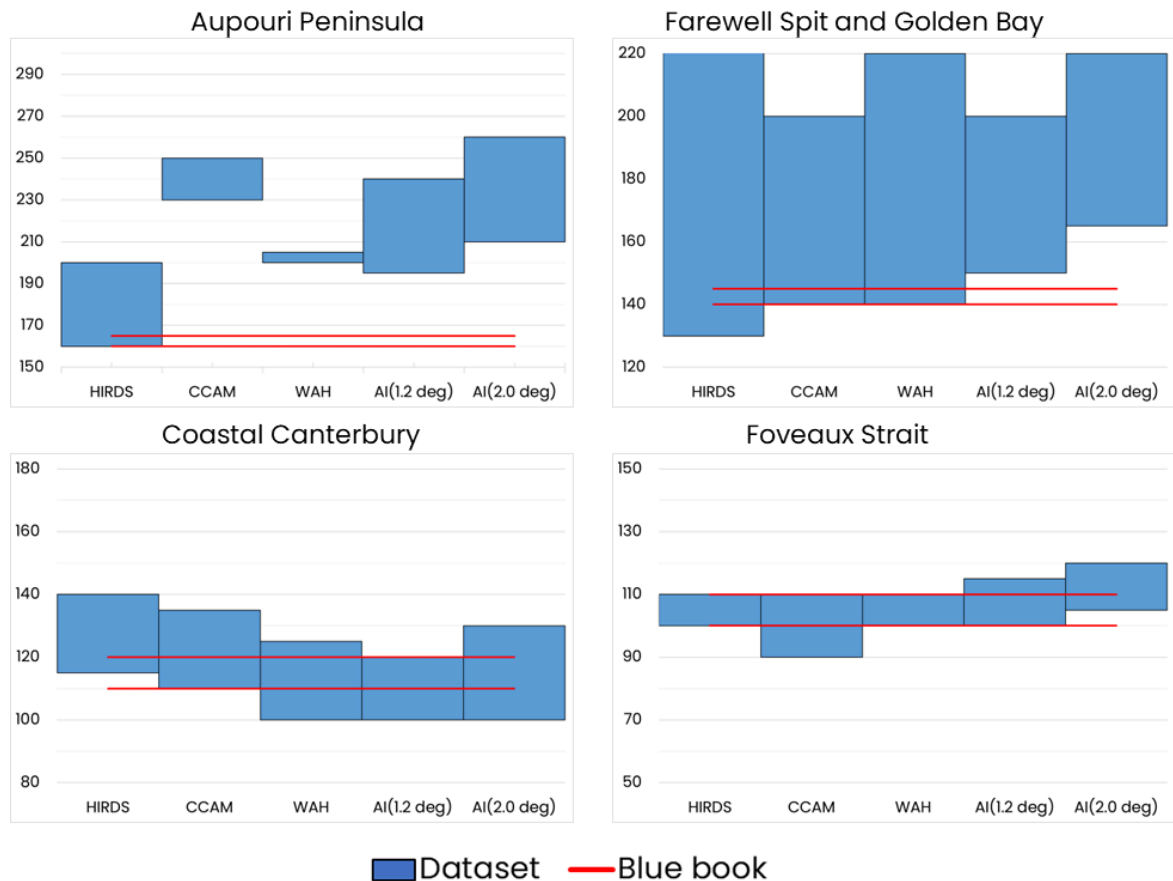


Figure 21: 1-in-100 year 24-hour convergence precipitation estimates (mm) over the four regions assumed in the Blue Book to have little orographic influence on precipitation across five of the data sets examined in this analysis. The CCAM values shown are the original (not bias corrected) values.

To better understand this anomaly, both in the Blue Book and in the HIRDS analysis (which also shows low convergence only precipitation over the Aupouri Peninsula), we examined more closely the data underlying these estimates. On the Aupouri Peninsula, HIRDS includes records from five precipitation gauges:

- The Cape Reinga AWS at the northwestern tip of the peninsula with a 100-year record from 1919 to the present; noting the gauge was relocated slightly in the 1980s.
- Two gauges along the centre of the peninsula with approximately 40-year records.
- One gauge stated to have a 40-year record, but which includes a 30-year gap (which was not considered).
- One gauge with less than 10 years of record (which was not considered).

In addition, Northland Regional Council has installed one additional gauge on the peninsula in the last 5 years (which was not considered).

Examination of 1-in-100 year 24-hour precipitation estimates from HIRDS at the gauge locations indicates that HIRDS is extrapolating to the west of the Cape Reinga AWS to get values below the 173mm derived for Cape Reinga (Figure 22). Furthermore, the HIRDS estimate of the 1-in-100 year precipitation depth near Cape Reinga AWS appears to be slightly lower than the other values on the peninsula (despite being at a similar elevation).

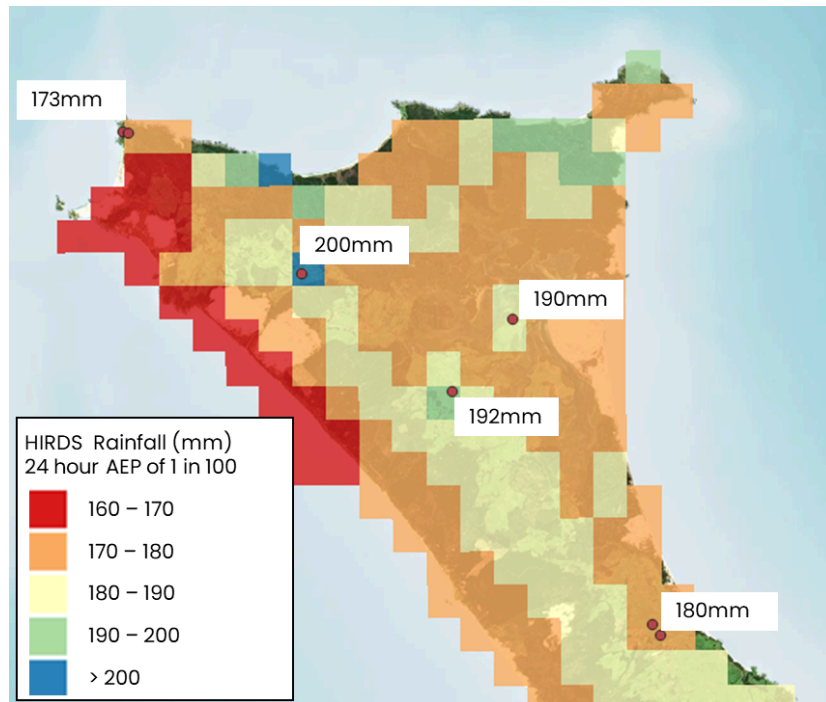


Figure 22: 1-in-100 year estimates of 24-hour precipitation over the Aupouri Peninsula from HIRDS. Both the site data (numerical values) and the spatially extrapolated field (colours) are shown.

To diagnose this lower than expected value, we have undertaken a site specific frequency analysis of the Cape Reinga AWS daily precipitation record (1919 to the present; Figure 23). Daily precipitation maxima were increased by 13% to approximate 24-hour maxima (see above). An extreme value analysis of these annual maxima indicated 1-in-100 year precipitation depths between 200mm and 230mm, suggesting that the value of 173mm is an under-estimate. The range of equivalent values derived from the other data sets was similar (see Figure 23).

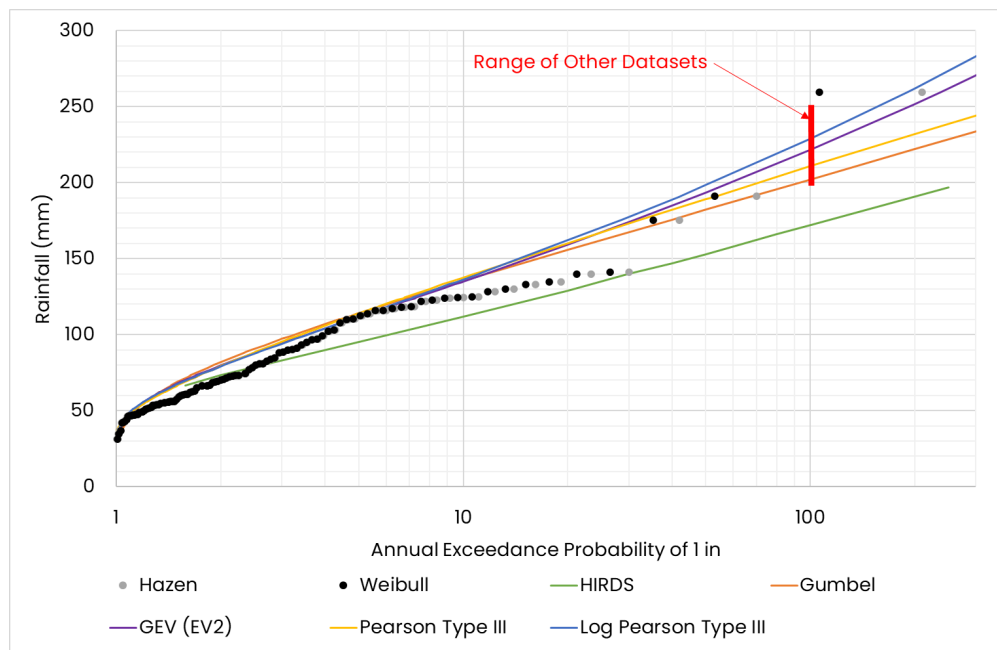


Figure 23: Site specific frequency analysis for the Cape Reinga AWS daily precipitation record.

The same analysis was repeated for the two gauges with 40-year records, i.e., the Te Paki Station (1931 to 1973) and Paua Blk Parengarenga (1970 to 2011); see Figures 24 and 25. The ranges of extreme value estimates were 220mm to 244mm and 210mm to 280mm respectively. Again, the range of the other data sets was within the expected range of the annual maxima. This adds additional evidence to the C_{100} values used in the Blue Book for Northland being underestimated and thereby negatively biasing the C_{100} field over the North Island.

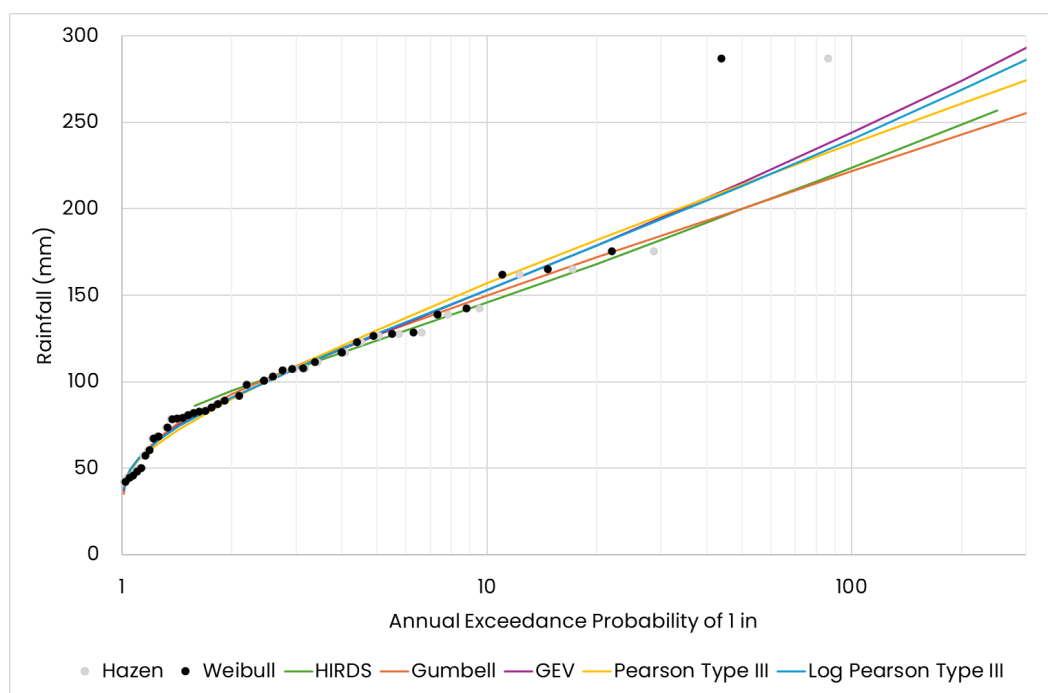


Figure 24: Site specific frequency analysis for the Te Paki Station daily precipitation record.

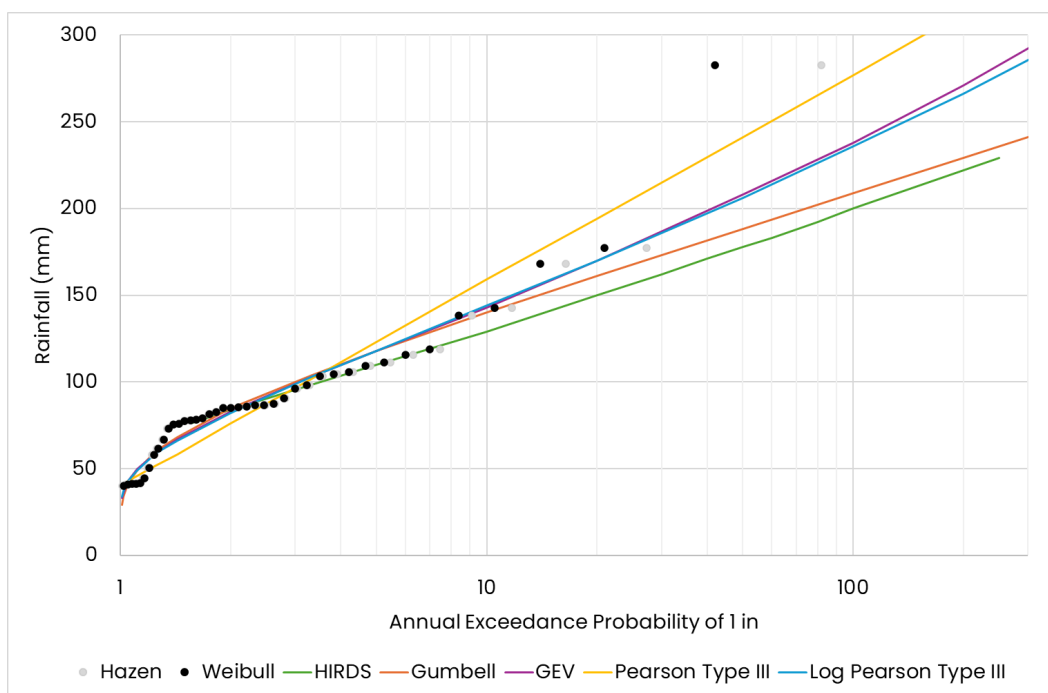


Figure 25: Site specific frequency analysis for the Paua Blk Parengarenga daily precipitation record.

As a prelude to deriving a C_{100} field from our selected T_{100} field (derived from gauge-corrected CCAM), we compared T_{100} fields from CCAM, bias corrected CCAM, and weather@home, with the Blue Book C_{100} field (see their Figures 6.16 and 6.17) after masking all regions with an orographic factor (as in the Blue Book) of greater than 1.0 (thereby masking areas subject to orographic influence on precipitation); see Figure 26.

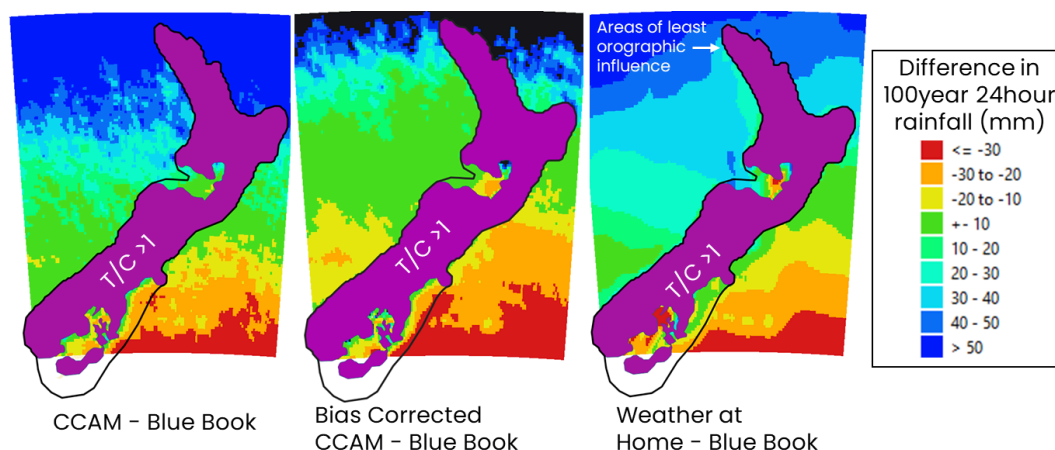


Figure 26: Differences in 1-in-100 year 24-hour convergence only precipitation between three of our data sets (x), over regions where it is assumed that $C_{100}=T_{100}$, against the Blue Book C_{100} field (x minus Blue Book).

The areas of least orographic influence were refined from those used in the Blue Book in two regions where the magnitude of C_{100} estimates changed rapidly (hypothesised to be a result of orographic effects). These were:

1. Between Farewell Spit and Mt Taranaki
2. Southeast of the South Island

Not unexpectedly, given the Blue Book underestimate of the C_{100} over Northland, all three data sets displayed in Figure 26 show a south to north gradient in their differences against the Blue Book C_{100} values, with differences exceeding 50mm in the far north. Interestingly, the differences between the three data sets and the Blue Book are rather small over much of the South Island, although are considerably negative to the southeast indicating lower values than the Blue Book in this region. We recommend that future studies test the sensitivity of the interpolated C_{100} field to the selected extent of minimal orographic influence.

After examining Figure 26, it was decided to conservatively use the region within the thin black line to denote the region where precipitation is potentially affected by orography. Therefore, to provide a C_{100} field over the landmass of New Zealand, the T_{100} field was masked within the black contour shown in Figure 26. To test the validity of different methods for estimating C_{100} values in the masked region, two interpolation methods were tested on both the CCAM and bias corrected CCAM T_{100} fields:

1. A simple linear interpolation.
2. Use the x-hour running mean 1-in-100 year gauge-corrected sea-level dew point temperature field (hereafter DPT) as the basis to interpolate across the masked region, where x is half the precipitation duration (12-hour running means used for 24-hour precipitation - see above).

For interpolation method (2), the regression model is constructed as:

$$CCAM_{i,j} = \alpha \times DPT_{i,j} + \beta \quad (17)$$

where α is expanded as:

$$\alpha = \alpha_0 + (\alpha_1 \times \phi) + (\alpha_2 \times \theta) + (\alpha_3 \times \theta \times \phi) + (\alpha_4 \times \phi^2) + (\alpha_5 \times \theta^2) \quad (17)$$

where ϕ is the latitude and θ is the longitude. β is expanded similarly. The resultant regression model has 12 fit coefficients. The original masked bias corrected CCAM 24-hour T_{100} field, the regression derived field, and the final resultant filled field are shown in Figure 27.

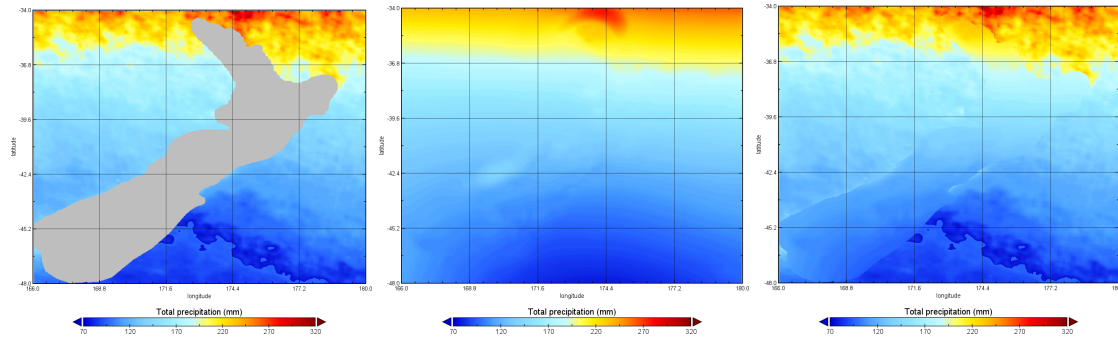


Figure 27: (left) The masked bias corrected CCAM 24-hour T_{100} field, (centre) the regression-modelled T_{100} field derived using the 12-hour 1-in-100 year gauge-corrected sea-level dew point temperature field (Figure 11) as a regression basis function, and the final filled field that constitutes the 24-hour C_{100} field. Note that when calculating PMP, only values over the land are used. Similar fields were derived for each target duration.

A comparison of the 24-hour C_{100} fields from the Blue Book, a simple spatial linear interpolation applied to the masked original CCAM T_{100} field, the dew point temperature based regression modelled CCAM T_{100} field, and the equivalent for the bias corrected CCAM T_{100} field, all constituting C_{100} fields, is shown in Figure 28.

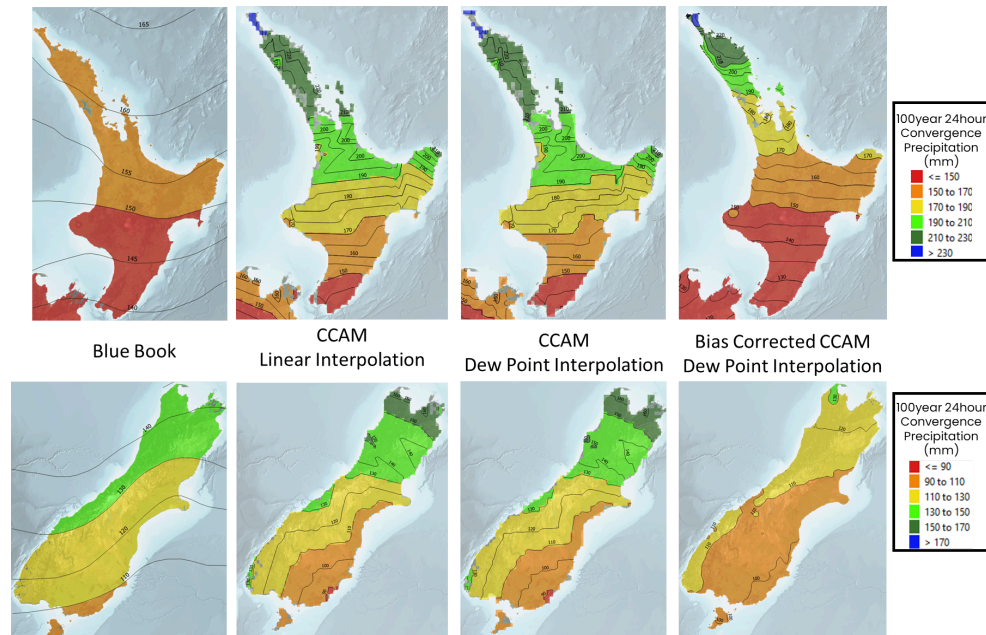


Figure 28: A comparison of C_{100} fields from the Blue Book and different interpolation techniques applied to masked original and bias corrected CCAM T_{100} fields to derive C_{100} fields.

The Blue Book somewhat optimistically suggested that there was an uncertainty range of around 5% (± 5 to 8mm) on their C_{100} field, which was attributed to the method of interpolation between estimates from areas of minimal orographic influence. Figure 29 highlights the differences between the Blue Book C_{100} field and those obtained from the original and bias corrected CCAM fields. C_{100} estimates are generally higher over the North Island and lower over the lower South Island. The largest differences are in the far north of Northland (70mm increase i.e., 40%) and the West Coast/Queenstown-Lakes District (25mm decrease i.e., 20%).

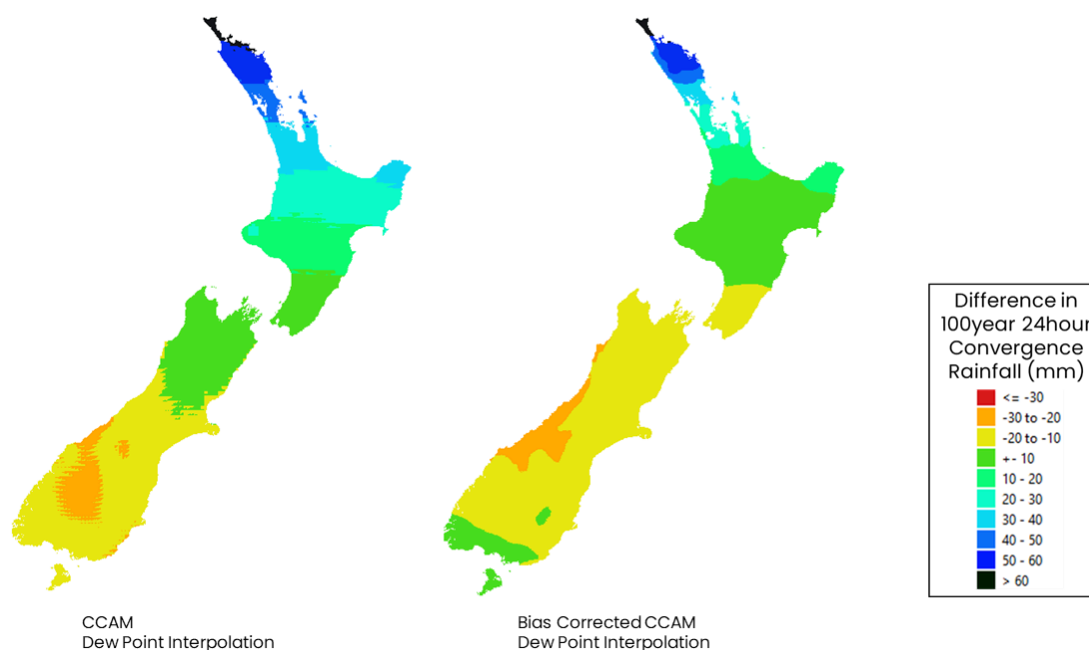


Figure 29: Differences between the 24-hour Blue Book C_{100} field and C_{100} fields derived from original (left) and bias corrected (right) CCAM (CCAM minus Blue Book).

This north-south gradient in the C_{100} field differences should not be surprising given the Blue Book C_{100} Northland anomaly noted above. The C_{100} fields used in the calculation of the index PMP fields (hereafter C_{100}) are those derived from bias corrected CCAM, i.e., the rightmost fields shown in Figure 28, consistent with the T_{100} fields also obtained from bias corrected CCAM.

Figure 21 is updated with estimates of C_{100} in each of the four regions of least orographic influence (black dashed lines), and the results of the gauge frequency analysis over the Aupouri Peninsula (light orange), in Figure 30. The updated estimates are toward the bottom of the range for most areas.

While we also considered deriving the CCAM C_{100} field using linear interpolation between the areas of minimal orographic effect, we did not fully progress with this approach as it appeared to give very similar results to the dew point interpolated fields. In future research, we recommend that new data sets are developed/investigated specifically for the purpose of estimating the convergence component of precipitation over New Zealand. Where reanalyses differentiate between different drivers (convergence and orography) of precipitation, these could provide direct estimates of the convergence component of precipitation. It may also be instructive to run models of precipitation over New Zealand where the topography is reduced uniformly over New Zealand to 1m.

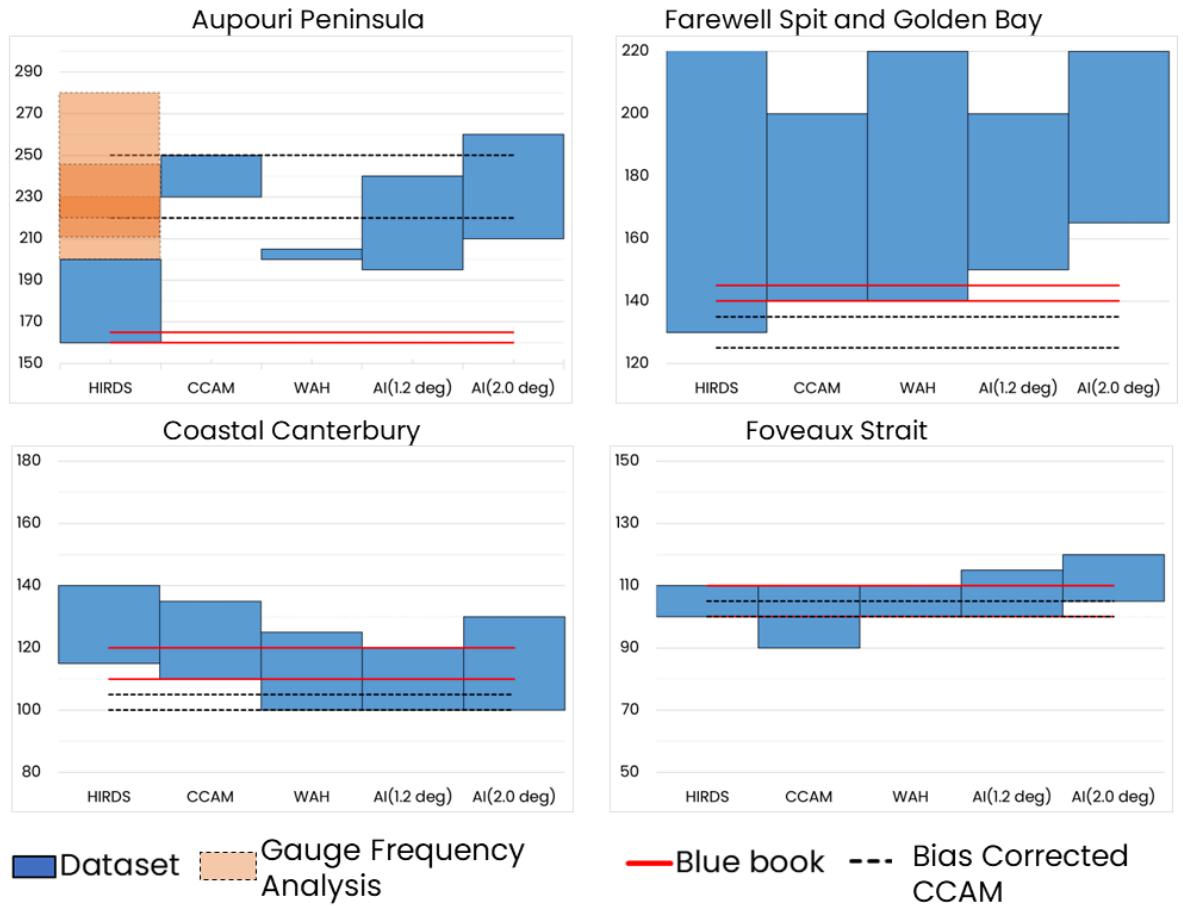


Figure 30: An updated version of Figure 21 now including values from bias corrected CCAM (black dashed lines) and the gauge frequency analysis over the Aupouri Peninsula (orange bars).

4.4.4 Orographic factor (T_{100}/C_{100})

Blue Book

The Blue Book uses the concept of storm separation (Hansen et al., 1977 & 1988) to derive an orographic factor (T_{100}/C_{100} , i.e., the proportion of precipitation attributed to orographic effects). We note that the concept of storm separation has not been critically reviewed (England et al., 2020). The Blue Book calculates the ratio of the 1-in-100 year total precipitation field (T_{100}) and the associated convergence precipitation field (C_{100}) using a 24-hour duration precipitation field. The use of a 100-year ARI was justified as storms maximised to obtain the PMP values in the Blue Book were thought to have an ARI of approximately 100 years. The Blue Book assumes that the T/C ratio derived for storms at 24-hour duration with an ARI of 100 years will also be relevant for storms of other durations and the more extreme ARIs associated with PMP events.

We have georeferenced and digitised the T/C field presented in the Blue Book onto a 1km x 1km grid using a Kriging interpolation. Values range from 1 in areas either toward the coastline or inland which are sheltered by orography, to 8 over the Southern Alps. Noting that the T_{100} and C_{100} fields presented in the Blue Book are presented by contour maps with rather coarse spacing between contours which degrade the true underlying point-based data set, dividing the digitised

Blue Book T_{100} field by the digitised C_{100} field generates a pattern slightly different from that obtained by digitising the T/C field presented in the Blue Book directly; differences are primarily a result of the resolution of the T_{100} field (especially over the southeast of the South Island).

MVP

While we ultimately settled on using the bias corrected CCAM T_{100} and C_{100} fields to calculate the orographic factor field, we examined several combinations of T_{100} and C_{100} fields to test for consistency and robustness of our selection. T_{100} fields from the following sources were considered:

- Blue Book (digitised contours from Figures 6.14 and 6.15 of the Blue Book)
- Blue Book (HIRDS T_{100} field used as a spatial interpolator for Blue Book T_{100} field)
- HIRDS
- nn-GEV field at 1.2°C of warming above pre-industrial
- nn-GEV field at 2.0°C of warming above pre-industrial
- The original CCAM field
- The bias corrected CCAM field

Each of these was divided by C_{100} fields from the following sources to obtain orographic factor fields:

- Blue book (Figures 6.16 and 6.17 of the Blue Book) - shown in Figure 31.
- The original CCAM field filled by dew point temperature interpolation (see 3rd column of Figure 28) - shown in Figure 32.
- The bias corrected CCAM field filled by dew point temperature interpolation (see 4th column of Figure 28) - shown in Figure 33.

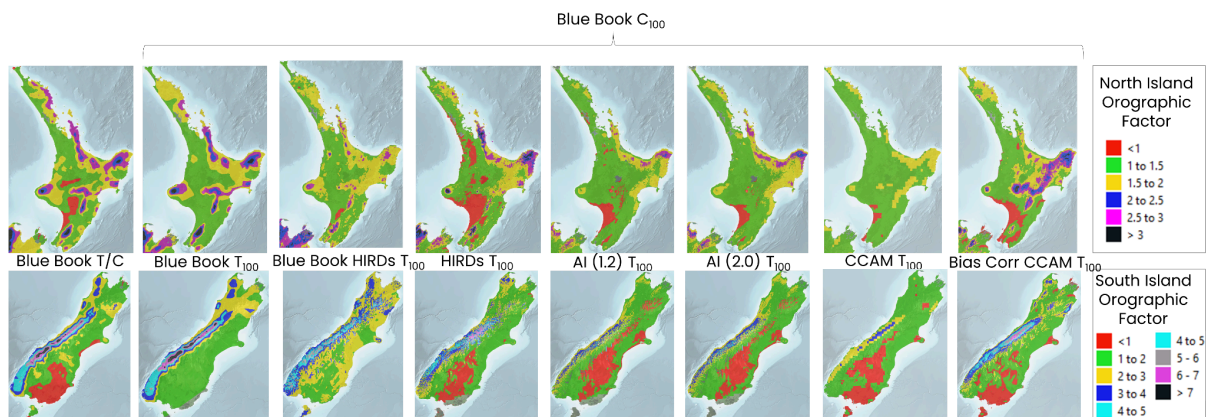


Figure 31: Orographic factor fields derived by dividing T_{100} fields from seven different sources (columns 2 to 8) by the Blue Book C_{100} field, compared to the orographic factor field digitised directly from the Blue Book (column 1; Blue Book Figures 6.18 and 6.19).

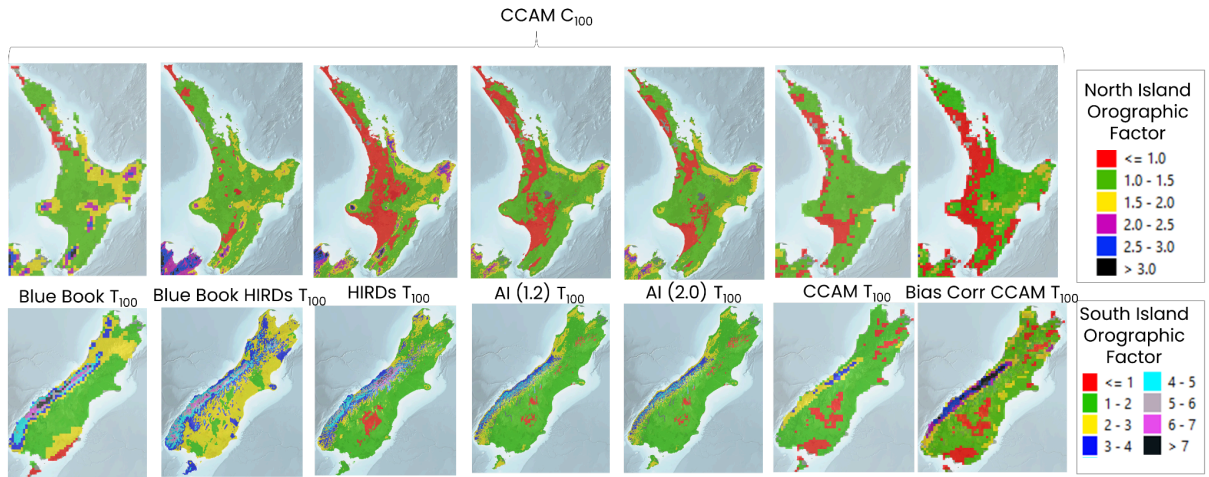


Figure 32: Orographic factor fields derived by dividing T_{100} fields from seven different sources by the original CCAM C_{100} field.

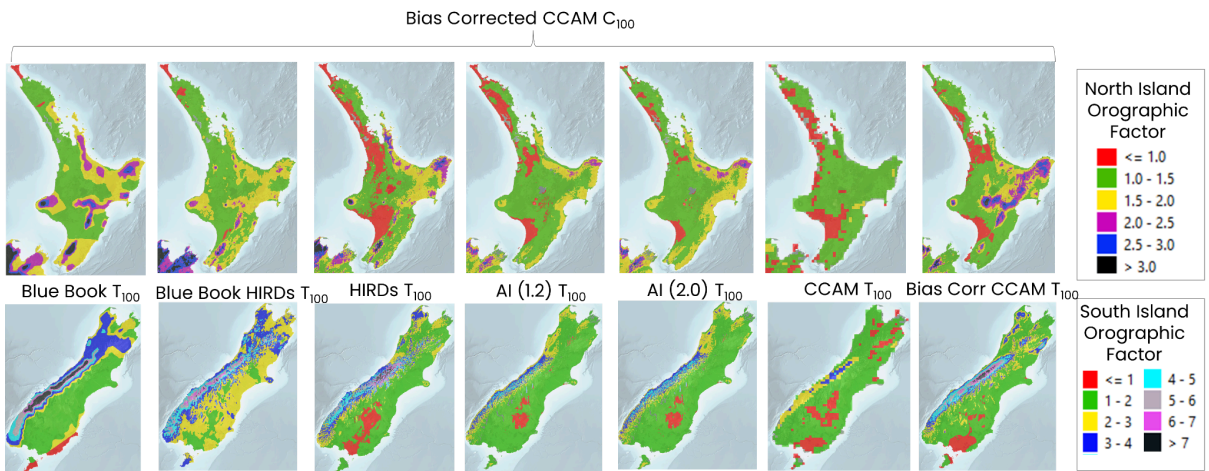


Figure 33: Orographic factor fields derived by dividing T_{100} fields from seven different sources by the bias corrected CCAM C_{100} field.

Careful examination of the results presented in Figures 31 to 33 increased our confidence in the choice of the bias corrected CCAM T_{100} and C_{100} fields for the calculation of the orographic factor field for use in the index PMP calculation (rightmost column in Figure 33).

To show more clearly the differences between the MVP T/C field and that provided in the Blue Book, absolute differences between these two fields are plotted in Figure 34. The MVP field generally has a lower amplitude than the Blue Book T/C field, with exceptions along the East Cape coast, the central North Island, and the south-east of the lower South Island. We recommend that further research is undertaken to both refine the estimation of the orographic factor, and to carry through the uncertainties associated with deriving the T_{100} and C_{100} fields to uncertainties in the orographic factor field.

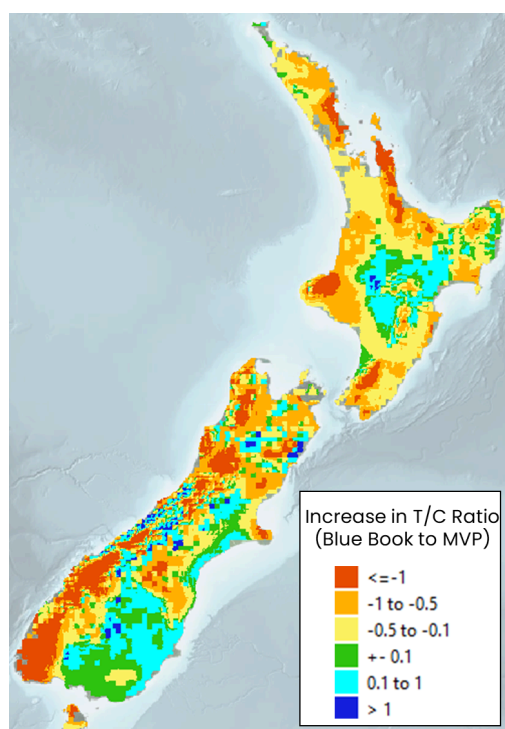


Figure 34: Differences in the orographic factor (T_{100}/C_{100}) field - bias corrected CCAM minus Blue Book.

Sensitivity to selected duration

Because CCAM provides precipitation fields at 1-hour temporal resolution, it was possible to calculate orographic factor fields for a range of durations (not just 24-hour duration as was the case in the Blue Book). Such fields for precipitation durations of 1, 6, 24, 48, 96 and 168 hours are shown in Figure 35.

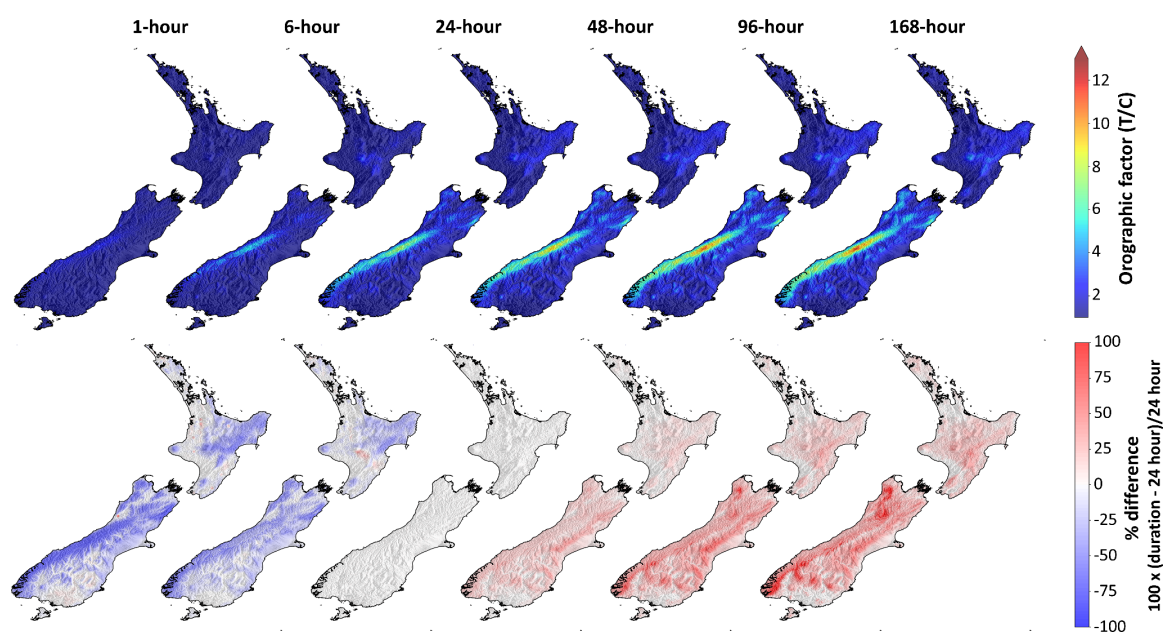


Figure 35: Sensitivity of the orographic factor field (T/C) to precipitation duration. The top row of panels shows the T/C fields for durations of 1, 6, 24, 48, 96 and 168 hours while the bottom row of panels shows the percentage difference with respect to the 24-hour duration field.

In general, orographic factor fields of lower amplitude are expected for storms of shorter duration while higher amplitude T/C fields are expected for storms of longer duration. This is not surprising as storms of different durations are likely to be caused by different meteorological conditions which will interact with the topography in different ways. We recommend that future studies explore more widely the dependence of the T/C field on precipitation duration.

Sensitivity to Selected AEP

The Blue Book considered only T and C fields of 100-year ARI. Cognisant that the orographic factor field may be ARI dependent, 24-hour precipitation T/C fields were calculated at ARIs of 20, 50, 100, 200, 1000 and 10000 years (Figure 36).

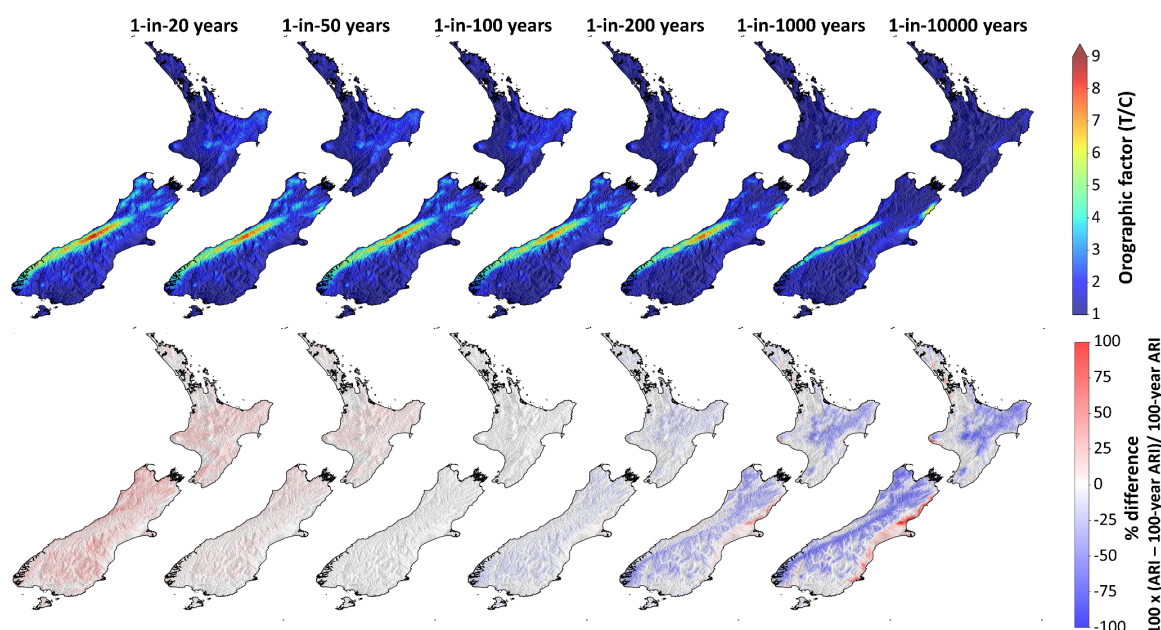


Figure 36: Sensitivity of the orographic factor field (T/C) to average recurrence interval (ARI). The top row of panels shows the T/C fields for ARIs of 20, 50, 100, 200, 1000 and 10000 years while the bottom row of panels shows the percentage difference with respect to the 100-year ARI field.

Other than over the east coast of the South Island, T/C fields tend to have lower amplitudes for rarer events (i.e., a higher proportion of the precipitation was caused by convergence). We recommend that future studies reconsider whether the T/C ratio is appropriate for application in New Zealand, and whether it may be possible for the T/C ratio to be calculated based on the estimated ARI of individual storms.

4.4.5 Storm catalogue - Estimating storm precipitation

Blue Book

Two separate storm catalogues, compiled from the New Zealand Meteorological Service pluviograph archives, were used in the Blue Book methodologies. Key attributes for these storms were used to derive:

1. The maximisation ratio (see equations 9 and 10). The value of 3.05 used in the Blue Book was derived from a 1% exceedance probability of $C_{\max}/C_{100}$ values from individual storms, where $C_{\max}$ is the 'maximised' convergence precipitation for the storm (see Section 4.4.9).
2. $C_{\max}$ - area-duration relationships to derive depth-area-duration curves.
3. The temporal pattern for each storm from which the storm intensification factor (m in equations 9 and 10) was derived.

The first storm catalogue considered storms with a duration of 24 hours (for use in the large areas and long durations PMP methodology). Thompson and Tomlinson (1989) lists the largest 100 events which were identified to have daily precipitation totals over 300mm. These were refined and added to, following consideration of flood producing capacity and taking into account findings from prior PMF and flood studies; McKerchar and Pearson (1989), Soil Conservation and Rivers Control Council (1957), Works Project Services (Freestone personal communication, 1990), Riddell (1980a, 1980b, 1981), Thompson and McGann (1990), Natusch (1972), Jowett and Thompson (1978), and DSIR (1988). This resulted in 94 storms in the catalogue with the 20 largest (determined on a depth-area basis) being analysed in detail. Daily storm precipitation for these 20 storms was plotted for precipitation gauges within the New Zealand Meteorological Service, DSIR Marine and Freshwater Division and Regional Councils databases for 1, 2 and 3 day periods. A contour surface was manually drawn around the gauge observations, and then digitised onto a 10km square grid. The grid was interpolated onto a 5km grid using a bi-cubic spline. Precipitation isohyets were then extracted from the 5km grid and used to calculate storm precipitation depth-duration-area estimates following the methodology outlined in WMO (1969).

The second storm catalogue considered storms with a duration of 1 hour (for use in the small areas and short durations methodology). Thompson and Tomlinson (1993) lists the largest 15 events which were identified as having hourly precipitation totals over 50mm and evidence of convective processes (reports of thunder, lightning or hail).

MVP

A periodic improvement to the first storm catalogue was considered, following the Blue Book process, to identify more recent events meeting the same criteria. An initial search was undertaken within the National Climate Database for daily storms which resulted in gauge observations greater than 300mm. This identified 114 new storms (in addition to the 94 identified in the Blue Book). Of these, 41 were in the period before 1989 but had not been identified in the Blue Book. This initial search also identified several limitations of the Blue Book storm catalogue generation procedure, which;

1. Does not account for the storm area, highlighting several events which were only observed at a single gauge. This was partially addressed later in the Blue Book by considering flood producing capacity.
2. Gives undue weight to storms in mountainous areas (refer to Figure 1), potentially excluding extreme storms in areas with lower orographic effect. Identifying storms by way of total precipitation will bias any storm catalogue to mountainous regions and may

omit severe storms elsewhere. In contrast, events from a storm catalogue compiled by way of convergence only precipitation would not have such a geographical bias.

3. By not considering C_{100} estimates, the Blue Book methodology is unlikely to select storms where convergence precipitation estimates are lower than other regions but where the ratio of maximised convergence precipitation (C_{max}) and C_{100} estimates is greatest.
4. Does not consider dew point temperatures in the selection of storms for inclusion in their storm catalogue and is therefore unlikely to select storms which occurred with especially low dew point temperatures, which, when maximised, would result in the largest total precipitation.

For the purposes of the MVP, a completely automated method was developed (hereafter the storm detection algorithm; SDA) and used to generate the storm catalogue and estimate the storm precipitation. Automating this process, rather than relying on manual compilation of storms as was done in the Blue Book, will also facilitate low-personnel-cost updating of the catalogue in the future.

The SDA was applied to the hourly gauge-corrected ERA5 precipitation fields described earlier in the report from 1950 to 2019. While the SDA can be applied to any user-prescribed precipitation duration, for the purposes of compiling the MVP storm catalogue, it was applied to 24-hour precipitation only. Before the precipitation fields were analysed, they were divided by the orographic factor (T_{100}/C_{100} ; see above) field to create 'convergence only' precipitation fields (C), thereby circumventing limitation (2) of the compilation of the Blue Book storm catalogue detailed above. The orographic factor field, at 1km resolution, was coarsened (by way of calculating area means) by a factor of 10 to align with the 10km resolution grid underlying the gauge-corrected ERA5 data set. For a given hourly C field, the SDA locates the cell with the highest value. It calculates the cell's area (which varies with latitude) and creates an entry in a database of that area and value (as well as various other values such as the total precipitation and the maximum persisting gauge-corrected sea-level dew point temperature in that cell). It then considers a 'two cell storm'. Because we define a 'storm' as a set of contiguous cells in a precipitation field, only the 8 neighbouring cells of the initial cell are considered as candidates for expansion. The neighbour with the highest precipitation is then appended to the 'storm', their total area calculated, the mean C and total precipitation (T) calculated, and this event is added to the database. Of course there is the possibility that a 'two cell storm' elsewhere in the country occurs where the mean precipitation is higher than the initial 'two cell storm' but where neither cell is the maximum in the C field over the whole country. Such cases are detected and a set of storms is compiled, each growing by one cell (considering all neighbours of cells in the $N-1^{th}$ sized storm and selecting the neighbour with the highest C value) as storms of increasing size are generated. This approach mitigates limitation (1) of the compilation of the Blue Book storm catalogue detailed above. Applying this algorithm to hourly C fields over the course of an event generates several hundred values of the average convergence only precipitation over a wide range of storm areas in the database for a single field C . The upper envelope of the C values plotted as a function of area provides a depth-area relationship for that hour. That envelope is then sampled via linear interpolation at 11 selected index areas: 100km², 500km², 1000km², 1500km², 2000km², 5000km², 7000km², 10000km², 12000km², 15000km², and

20000km². Figure 37 shows an example of those convergence only precipitation values for those 11 index areas over the course of Cyclone Bola which impacted the East Cape in March of 1988.

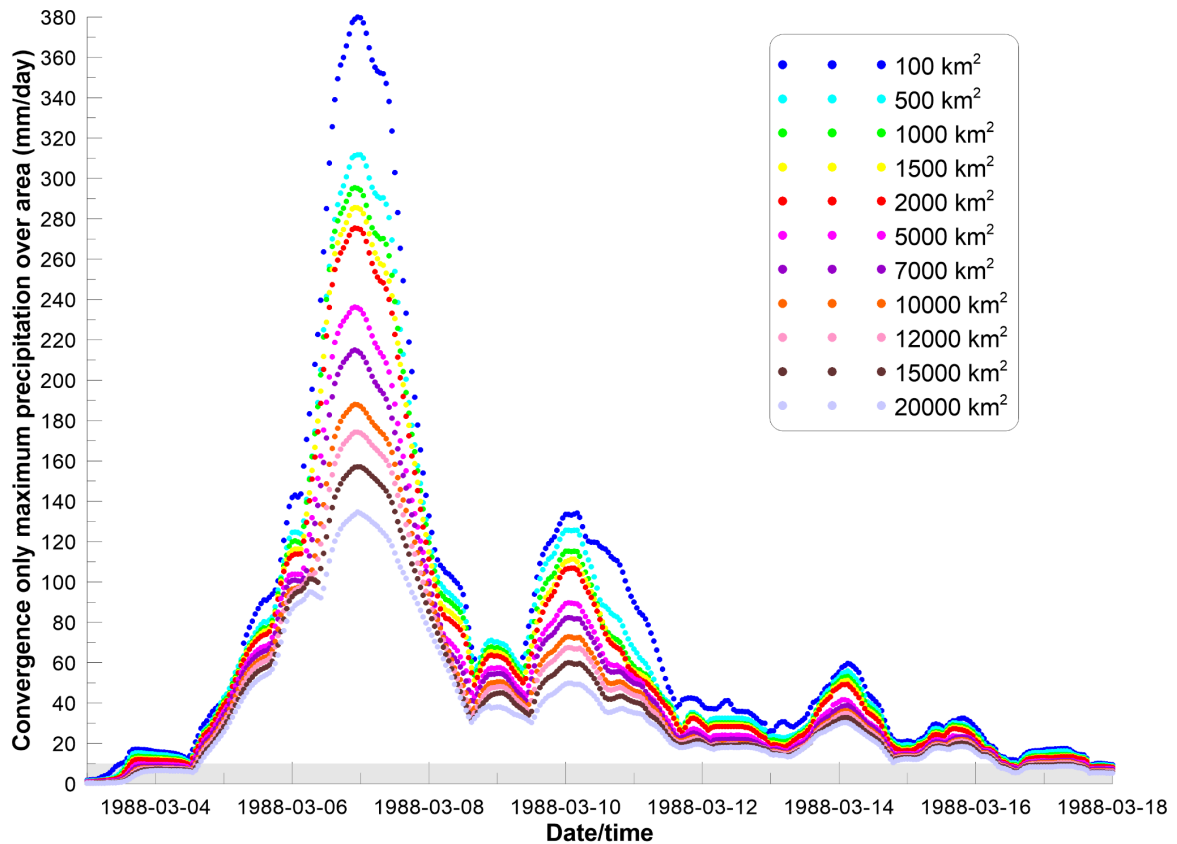


Figure 37: An example of the time series of convergence only precipitation generated for 11 different index storm areas over the course of Cyclone Bola.

Hourly time series, such as those shown in Figure 37, were generated for each year from 1950 to 2019. These time series were used to identify ‘events’ for each of the 11 index areas, where an ‘event’ is defined as a continuous period (in time) where, for a given index area (e.g., 100km²), the precipitation remains above a defined threshold (in this case 10mm/day - shown by the grey region in Figure 37). The ‘size’ of an event is then defined as the area under the curve above the 10mm/day threshold. This results in several hundred events of varying sizes for each index area. The largest 50 events for each index area were then considered. With 11 index areas this results in a total of 550 ‘largest’ events - though many of these temporally overlap. Where they overlap, the earliest start date and latest end date (out of the 11 traces, e.g., as shown in Figure 37) are found to obtain a single compound event. Once those overlapping events have been combined, we are left with a database of 97 events that comprise our best estimate of the largest convergence only precipitation events over New Zealand over the period for which the gauge-corrected ERA5 data are available. This database comprises the MVP storm catalogue as an alternative to that used in the Blue Book. Of those 97 events, 82 occurred between 1960 and 2019 (the period for which we had the gauge-corrected sea-level dew point temperature field required to calculate the moisture maximisation; Appendix D).

While these events were identified based on 24-hour precipitation, they were then also used to obtain key attributes of these 97 storms for other precipitation durations (1, 3, 6, 12, 24, 36, 48, 72, 84, 96, 120, 168 hours). These attributes were:

1. The start date and time of the event.
2. The end date and time of the event.

A definition of the geographical extent of the event derived from the 100 'hottest' pixels in heat maps generated by the SDA code:

3. The minimum (southern-most) latitude of the event.
4. The maximum (northern-most) latitude of the event.
5. The minimum (western-most) longitude of the event.
6. The maximum (eastern-most) longitude of the event.

And then for each of the index areas A:

7. The 'upper-envelope' (i.e., maximum experienced over the period of the event) convergence only precipitation calculated as the mean over an area of $A\text{km}^2$.
8. The 'upper-envelope' C_{100} value for the event, calculated as the mean over an area of $A\text{km}^2$, sampled from the same cells used to track the convergence only precipitation.
9. The 'upper-envelope' seasonal maximum (described below) of the 1-in-100 year gauge-corrected sea-level dew point temperatures values, over an area of $A\text{km}^2$, sampled from the same cells used to track the convergence only precipitation.

Three measures of the storm dew point temperature (described further below). While only the mean was used, all three were tracked in case it was decided to use the maximum or minimum as an alternative:

10. The mean of the gauge-corrected sea-level dew point temperatures, over an area of $A\text{km}^2$, sampled from the same cells used to track the convergence only precipitation.
11. The maximum of the gauge-corrected sea-level dew point temperatures, over an area of $A\text{km}^2$, sampled from the same cells used to track the convergence only precipitation.
12. The minimum of the gauge-corrected sea-level dew point temperatures, over an area of $A\text{km}^2$, sampled from the same cells used to track the convergence only precipitation.

And finally three derived quantities based on the preceding attributes:

13. The ratio that was used to scale the convergence only precipitation (7) to get the maximised convergence precipitation (14).
14. The *maximised* convergence only precipitation of the event based on a 200hPa precipitable water lookup table and using the gauge-corrected sea-level dew point temperatures from (10); this 'moisture maximisation' is described in Section 4.4.9.
15. The resultant maximisation ratio (C_{max}/C_{100}); (14) divided by (8).

Tables of convergence precipitation depth for storms from our updated storm catalogue are summarised at various durations and areas and are available on request from the author. While we believe our storm catalogue is a significant improvement over that used in the Blue Book, several avenues for further improvement remain, e.g.:

- Updating the storm catalogue to ensure it has captured the largest events at index durations other than 24 hours.
- Taking the convergence only precipitation fields, derived by dividing the ERA5 gauge-corrected fields by T_{100}/C_{100} , and maximising this convergence precipitation over the whole time series using the moisture maximisation process defined below. Detecting

large events in the resultant fields may result in a more robust storm catalogue. This would also mitigate limitation (4) of the Blue Book.

- Rather than deriving the storm catalogue by searching for large (both in space and time) convergence only precipitation events, the maximised observed total precipitation (based on total precipitable water scaling; see below) could be divided by C_{100} estimates and maxima in those ratios could be used to define large events. This would also mitigate limitation (3) of the Blue Book.
- Refine the storm precipitation reconstruction perhaps by considering alternative or higher spatial/temporal resolution gridded data sets, or the application of bespoke weather model simulations for specific events.
- Updating the storm catalogue to the present to include recent notable events such as Cyclone Gabrielle and the 2023 Auckland Anniversary Day floods.

4.4.6 Storm catalogue - Estimating storm dew point temperatures

Blue Book

In the Blue Book, a single representative 12-hour maximum (as in highest value during the storm) persisting dew point temperature estimate was identified for each of the 94 storms detailed in their storm catalogue. The location for a representative dew point temperature estimate was selected from the warm air inflow region of the storm which was identified from both synoptic charts and upper level wind flow charts. It was noted that while it is desirable to have estimates outside the precipitation area (where dew point temperatures may be too high), this could not always be undertaken (due to the absence of data over the oceans surrounding New Zealand). Individual dew point temperature values were primarily obtained from daily observations (at 9am) at meteorological stations and were supplemented using tephigrams (where available). Dew point temperature values from daily observations were lowered by half a degree following a deviation identified at Auckland and Hokitika where the 9am dew point temperature was found to be 0.5°C to 1°C higher than the 12-hour persisting dew point temperature.

MVP

Storm dew point temperatures were extracted from the same hourly gauge-corrected sea-level ERA5 data set which was used to estimate maximum dew point temperatures (see Section 4.4.1), taking the average within a sliding window whose width was half the duration of the precipitation (see Section 4.4.3). As detailed in Section 4.4.5, to estimate the storm average dew point temperature for every event in our updated storm catalogue, we selected the average dew point temperature from the same area associated with the highest convergence precipitation. An initial comparison was conducted of maximised (100-year ARI) 12-hour average dew point temperatures and Blue Book 12-hour persisting dew point temperature estimates, for 13 of the 20 events which were selected for detailed analysis (Appendix B, Figures B-1 and B-2). Seven events were not compared as they occurred prior to 1960 during a period where gauge-corrected sea-level dew point temperatures were not available (as we did not have access to National Climate Database dew point temperature data prior to 1960) or did not appear in our storm catalogue. For each event window defined in the Blue Book, the difference between the *single* Blue Book dew point temperature estimate and the *map* of gauge-corrected ERA5

dew point temperatures, is shown (Appendix B). Estimates were generally within 1°C for North Island storms and within 2°C degrees (-1.3°C to 2.6°C) for South Island storms - noting that only sea-level values have been compared. In considering these 13 events for storm dew point temperature verification, it was noted that areas of high precipitation generally tended to have slightly higher dew point temperatures than over the identified Blue Book moisture source areas. There also tended to be considerable spatial variability in the dew point temperatures over both the precipitation area and the moisture source area. Bearing in mind that there is typically 1-2°C of uncertainty in estimating a maximum persisting dew point temperature for an event, we have selected to use the ERA5 estimates of maximum average dew point temperature in the updated storm catalogue.

We recommend that future studies investigate, for each event in the storm catalogue, defining a region that encompasses the warm air moisture inflow that causes the extreme precipitation. We hypothesise that precipitable water associated with the dew point temperature adiabat over that region would provide a better estimate of the storm precipitable water, and that this process could be iterated over to derive different maximisation factors across the wider storm area. We note that this region might cover different extents at different altitudes (refer to discussion in Section 4.4.1).

4.4.7 Storm catalogue - Estimating storm C_{100}

Blue Book

The Blue Book took the C_{100} estimate at each selected gauge location to represent the C_{100} field within each storm.

MVP

As detailed in Section 4.4.5, to estimate the C_{100} value associated with each event in the MVP updated storm catalogue, we averaged values from the bias corrected CCAM C_{100} field over the same precipitation areas associated with the highest convergence precipitation. These storm catalogue C_{100} values are available for each index area and each target duration.

4.4.8 Storm catalogue - Estimating storm 'season maximum' dew point temperatures

Blue Book

To estimate the maximum persisting dew point temperature associated with a storm event, the Blue Book interpolated, on the basis of latitude, between calendar month frequency analysis of data from 11 weather stations (Section 4.4.1). They then selected the 1-in-100 year dew point temperatures for each month, and took the maximum of those within each of four seasons:

1. **Summer:** December, January, February, March
2. **Autumn:** April, May
3. **Winter:** June, July, August, September
4. **Spring:** October, November

For example, if the storm occurred between the 1 April and 31 May, the largest of the two 1-in-100 year values (for April and May) was selected as the ‘season maximum’ dew point temperature for that storm.

MVP

To estimate the maximum expected dew point temperature for a given storm within our updated storm catalogue, the ‘season’ associated with the storm was the month(s) during which the storm occurred, as well as the two shoulder months. The maximum of the 1-in-100 year gauge-corrected sea-level dew point temperature over those N months (see Section 4.4.1 and Figure 11) was then calculated and the mean over the convergence only precipitation cells comprising the storm was calculated (Section 4.4.5). We consider this to be an improvement on the seasonal approach used in the Blue Book since, for example, a storm occurring right at the end of spring (e.g., 31 November), would now likely end up with the December maximum dew point temperature, whereas, following the Blue Book methodology, it would be limited to the value from November. However, we recommend that future studies, should they decide to use a moisture maximisation approach in their methodology, explore more scientifically robust ways of estimating an ‘extreme’ dew point temperature to be associated with each storm.

4.4.9 Moisture maximisation ratio

Blue Book

The Blue Book calculated their storm maximised convergence precipitation (C_{max}) as:

$$C_{max} = C_{storm} \times \frac{PW_{storm}}{PW_{1-in-100}} \quad (19)$$

where C_{storm} is the convergence precipitation associated with the storm (Section 4.4.5), PW_{storm} is the total precipitable water associated with the storm and is calculated from the storm dew point temperature (Section 4.4.6) and $PW_{1-in-100}$ is the total precipitable water associated with the storm ‘season maximum’ dew point temperature. The maximisation ratio (MR in equations 9 and 10) is then C_{max}/C_{100} , where the derivation of C_{100} is described in Section 4.4.7. Table 6.1 in the Blue Book was used to derive precipitable water from sea-level (1000hPa) dew point temperatures (reproduced below as Table 4).

Table 4: Precipitable water (mm) between 1000hPa and the indicated height - reproduced from Table 6.1 of the Blue Book.

Height (m)	1000 hPa dew point temperature (°C)			
	10	15	20	25
1000	8	11	15	21
2000	13	19	27	37
3000	17	25	35	50
5000	20	31	46	67
10000	21	33	52	80

A five step process was then undertaken to estimate the moisture maximisation ratio:

1. Estimate a representative storm persisting dew point temperature at 1000hPa assuming a pseudo-adiabatic atmosphere.
2. Estimate the storm precipitable water associated with the representative storm dew point temperature using the values from Table 4 above.
3. Estimate the season maximum persisting dew point temperature for the same location.
4. Estimate the season maximum precipitable water associated with the representative maximum dew point temperature, again using the values from Table 4 above.
5. Calculate the ratio of the storm maximum precipitable water to the season maximum precipitable water, to generate the moisture maximisation ratio.

Moisture maximisation ratios were limited to 1.8 as it was hypothesised that greater increases in moisture would affect the dynamical structure of the storm (Hansen et al., 1988; Kennedy, pers comm).

MVP

We have calculated moisture maximisation ratios in the same way as in the Blue Book. However, rather than using the values listed in Table 4, we have used a more recent table, viz. Table A.1.1 from WMO (2009). The following functions were found to approximate well the total precipitable water from the surface to 200hPa, which is expected to cover the majority of the column:

$$8.31672 \times e^{(0.092096 \times DPT)} \text{ for } DPT \leq 22^\circ\text{C}$$

and

$$9.55181 \times e^{(0.085416 \times DPT)} \text{ for } DPT > 22^\circ\text{C} \quad (20)$$

where DPT is the surface dew point temperature.

Moisture maximisation ratios for 12 events which were in both the wider Blue Book storm catalogue and our updated storm catalogue, are compared in Tables B-1 and B-2 in Appendix B. For some of these events, the derived ratios were quite similar, while somewhat different in others. We note that the rationale implemented in the Blue Book for limiting moisture maximisation ratios to 1.8 appears to be somewhat arbitrary, and has not been investigated in a New Zealand context. A change in this limiting value can be expected to have effects for most storm areas and durations (e.g., at the 24-hour 100km² index duration, 9 storms were capped by this value). We recommend that the utility and physical justification of applying a cap to moisture maximisation ratios be investigated in the context of New Zealand conditions.

4.4.10 Storm maximisation

The estimate of storm convergence precipitation was multiplied by the moisture maximisation factor to obtain an estimate of maximised moisture for each storm (see equation 19). The Blue Book methodology does not consider wind maximisation even though, as stated in WMO (2009):

‘wind maximisation is most commonly used in orographic regions when it appears that observed storm rainfall over a mountain range might vary in proportion to the speed of the moisture-bearing wind blowing against the range’

We recommend that wind maximisation, and factors in addition to dew point temperature, are investigated for application to PMP in New Zealand, e.g., the size/presence of blocking highs.

4.4.11 Estimating convergence PMP

Blue Book

The Blue Book settled on a maximisation ratio (MR in equations 9 and 10) of 3.05. The ratio was selected at the 1% significance level (i.e., a higher value than the highest storm catalogue ratio) of ratios of C_{max} to C_{100} in their storm catalogue, assuming that the highest 9 ratios (those greater than 2.5) were normally distributed (see Figure 38). No latitudinal dependence was identified in this distribution.

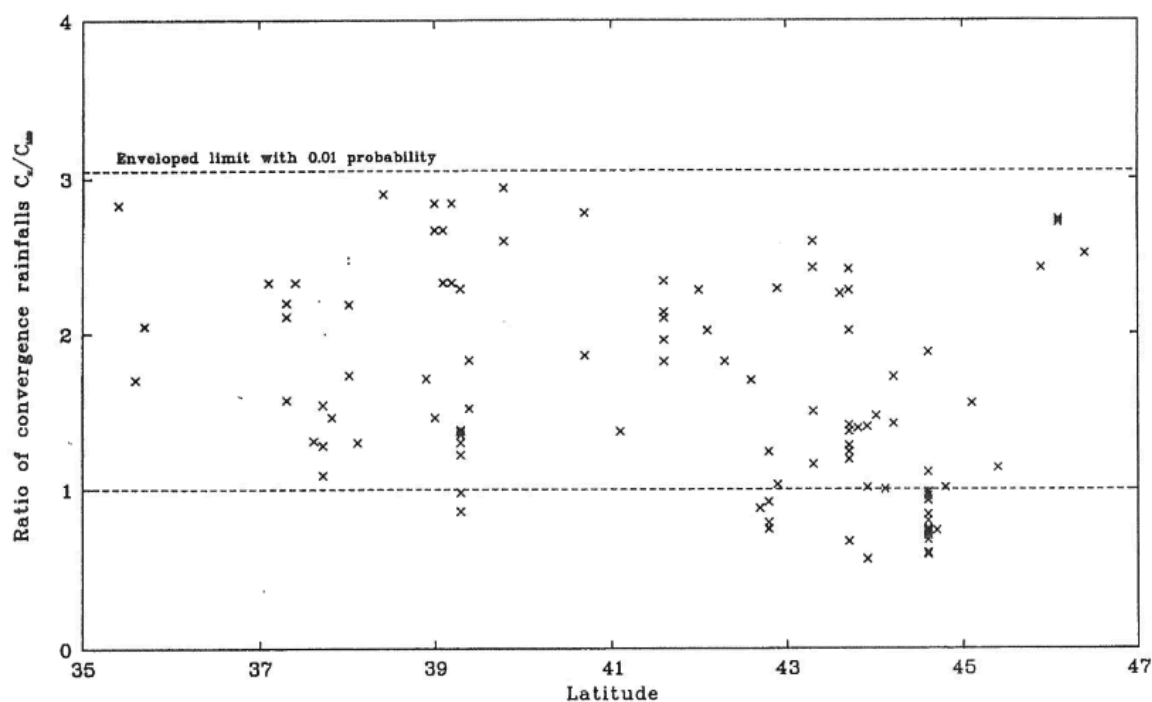


Figure 38: Ratios of *maximised* convergence precipitation to the 1-in-100 year convergence precipitation for each storm in the Blue Book catalogue - Figure 7.1 of the Blue Book

To get values for maximised 24-hour convergence only precipitation, the Blue Book selected the highest daily precipitation gauge totals from the 94 storms within their storm catalogue. It increased the values by 14% to approximate 24-hour totals, then divided them by the estimated T_{100}/C_{100} to estimate the highest 24-hour convergence totals. These were then maximised based on the ratio of maximum precipitable water associated with sea level dew point temperatures from the storm event, and seasonal maximums (as detailed in Section 4.4.9).

MVP

We have calculated similar C_{max}/C_{100} ratios for the storms in our updated storm catalogue. Given the uncertainty in estimating 25km^2 values from 100km^2 cells (as this was the approximate cell size in the $0.1^\circ \times 0.1^\circ$ hourly gauge-corrected ERA5 precipitation fields that we used for this purpose), we focus on C_{max}/C_{100} ratios from a 100km^2 index area. The calculated ratios for 24-hour precipitation are shown in Figure 39; no dependence on latitude or longitude was identified.

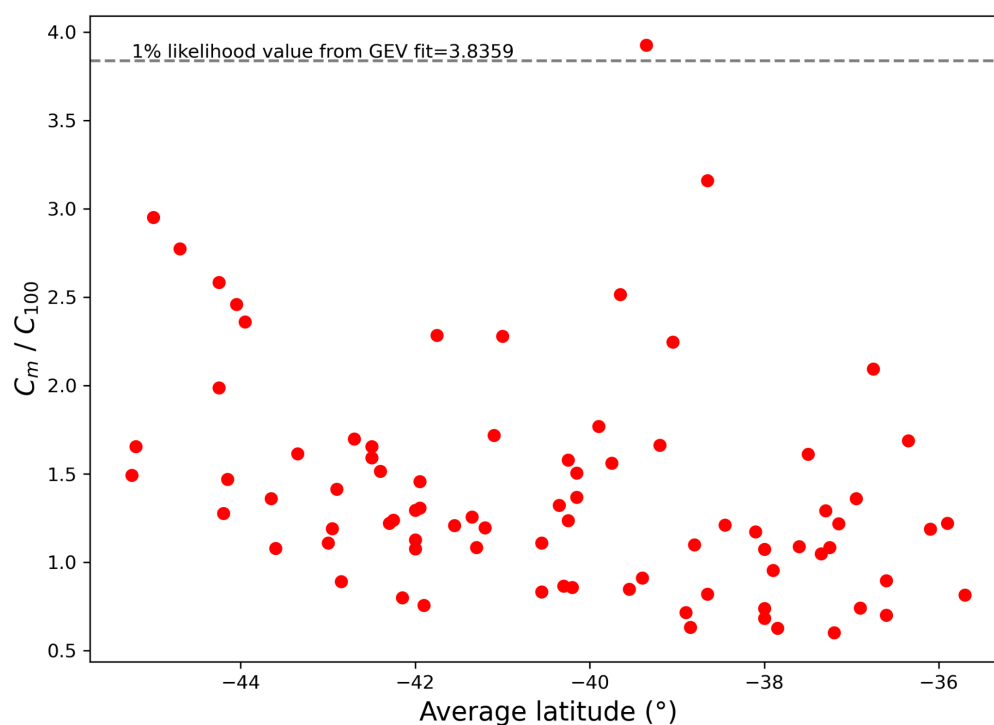


Figure 39: Ratios of 24-hour $C_{\max}$ to C_{100} vs. latitude, for 100km² index area, for the 82 storms for which these values are available in our storm catalogue

At 24-hour duration, the highest $C_{\max}/C_{100}$ ratio values for 25km² and 100km² areas were identified as two Gisborne events (Table 5) which both had values higher than the 3.05 1% significance level calculated in the Blue Book. An increase in $C_{\max}/C_{100}$ ratios was not unexpected given that the Blue Book selected $C_{\max}/C_{100}$ ratios from events which recorded the highest daily total precipitation (rather than convergence only precipitation) at gauge locations. Furthermore, we have selected events with the highest 24-hour convergence only precipitation from a gridded reanalysis which covers the entire country.

Table 5: The largest identified $C_{\max}/C_{100}$ ratios for 24-hour duration

Rank			Date	Island	Region	$C_{\max}/C_{100}$	
	25km ²	100km ²				25km ²	100km ²
1	1		May 1989	North	Gisborne	4.11	4.05
2	2		March 1988 (Cyclone Bola)	North	Gisborne	3.37	3.22
3	3		November 1999	South	S Otago	2.91	2.84
4	4		May 2010	South	Otago	2.87	2.81
7	5		June 1985	North	Taranaki	2.56	2.53
5	8		January 2002	South	S Canterbury	2.76	2.41
6	6		March 1965	South	S Westland	2.59	2.48

Furthermore, the May 1989 event did not appear at all in the Blue Book storm catalogue which may not be too surprising given that it was centred primarily between Wairoa and the Mahia Peninsula (an area with few precipitation gauges). The event convergence precipitation over an area of 100km² was identified to be approximately 370mm, which was slightly lower than the

same value derived for Cyclone Bola of 380mm. However, the moisture maximisation ratio of 1.78 was much higher than the 1.44 derived from Cyclone Bola and the storm C_{100} value was slightly lower.

The $C_{\max}/C_{100}$ ratio calculated for Cyclone Bola was 3.22, which was slightly higher than the ratio calculated in the Blue Book of approximately 2.9. This is largely a result of the selected precipitation area, which, in the Blue Book, came from the area of highest total precipitation, whereas we selected the area of highest convergence precipitation. For this event, the calculated moisture maximisation ratio is approximately 10% lower than that applied in the Blue Book. We have fitted extreme value distributions to all 82 of the $C_{\max}/C_{100}$ ratios. We note that the Blue Book selected to only take into account the highest 10% of their ratios (those above a value of 2.5), which reduced the sample to less than 10 events. From the extreme value distributions, we extracted the 1% likelihood value as was done in the Blue Book. One such value, derived from application of a GEV fit, is shown in Figure 39. Values from other distributions ranged from 2.89 to 4.27. After some deliberation, we settled on an expert-judgement-derived factor of 3.6. We note that this is lower than the ratio indicated for the May 1989 event, but considerably higher than the ratio indicated by other events. We recommend that detailed analysis is undertaken to better quantify precipitation and dew point values for the largest identified storm events. If values from the May 1989 event are to be believed, this could increase estimates of 24-hour index PMP by 15 to 20% everywhere around New Zealand.

As is clear from equations 9 and 10, the 24-hour index PMP scales directly with the maximisation ratio. Had we adopted a value of 3.05, this would generate 24-hour index PMP estimates which are generally lower than those in the Blue Book; adopting a higher value of 4.10 or greater (which the May 1989 event shows may potentially be possible) would result in large increases in 24-hour index PMP compared to the Blue Book values across most of the country (Figure 40).

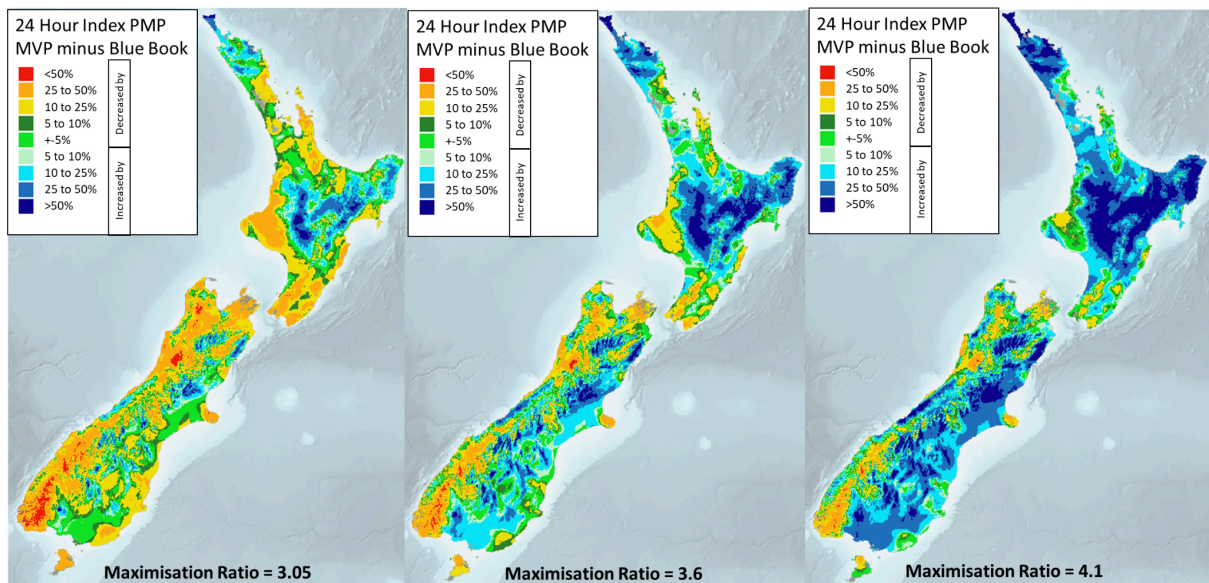


Figure 40: The dependence of the differences in the 24-hour index PMP field to the Blue Book on the selected maximisation ratio.

4.4.12 Evaluation of the storm intensification factor (m)

Blue Book

The storm intensification factor (m in equations 9 and 10) is defined as the ratio of the precipitation in the core time period of the storm to the total storm precipitation. In the Blue Book, this factor was defined as the proportion of the PMP temporal pattern where the precipitation intensity exceeded the average intensity. The Blue Book derived different storm intensification factors for the North Island and the South Island (see their Table 6.4 which is reproduced as Table 6 below).

Table 6: Storm intensification factor (m) - Blue Book Table 6.4

Island	Parameter	Storm duration (hours)				
		6	12	24	48	72
North	Core time period (hours)	3.5	6	9	14	17
	Storm intensification factor (m)	0.68	0.63	0.58	0.54	0.53
South	Core time period (hours)	3.5	6	9	11	14
	Storm intensification factor (m)	0.66	0.65	0.64	0.6	0.59

MVP

We have not altered the storm intensification factor from the Blue Book and have simply adopted the same factors. We note that the use of an average precipitation intensity as the threshold to define the storm intensification factor is somewhat arbitrary and recommend that future studies consider selecting a better, scientifically justified, threshold. We also recommend that future studies consider the sensitivity of the factor to both front and back weighted temporal patterns as well as the selected storm area.

4.5 Adjustment for elevation

Blue Book

The Blue Book acknowledges that sea-level convergence PMP needs to be reduced to account for the effects of topography between the moisture source and a catchment. It suggests applying a relatively constant decrease of 15% per kilometre of altitude as derived in HMR 43 (United States Weather Bureau (USBR), 1966). That said, the decrease applied in the Blue Book differed slightly from HMR 43 (see Figure 41). While the HMR 43 recommendations were only intended to be applied to windward slopes, the Blue Book also applied these to leeward slopes. HMR 43 was intended to be used up to elevations of around 2500m (8000ft); the Blue Book appears to have implemented a more conservative reduction for elevations above 2500m (although this is not discussed anywhere in the Blue Book). While HMR 43 recommended using the moist adiabatic rate of decrease up to the effective dew point temperature elevation, this was not implemented in the Blue Book methodology. When applying these reductions, the Blue Book recommends selecting an effective barrier height (Section 3.2: Adjustment for elevation).

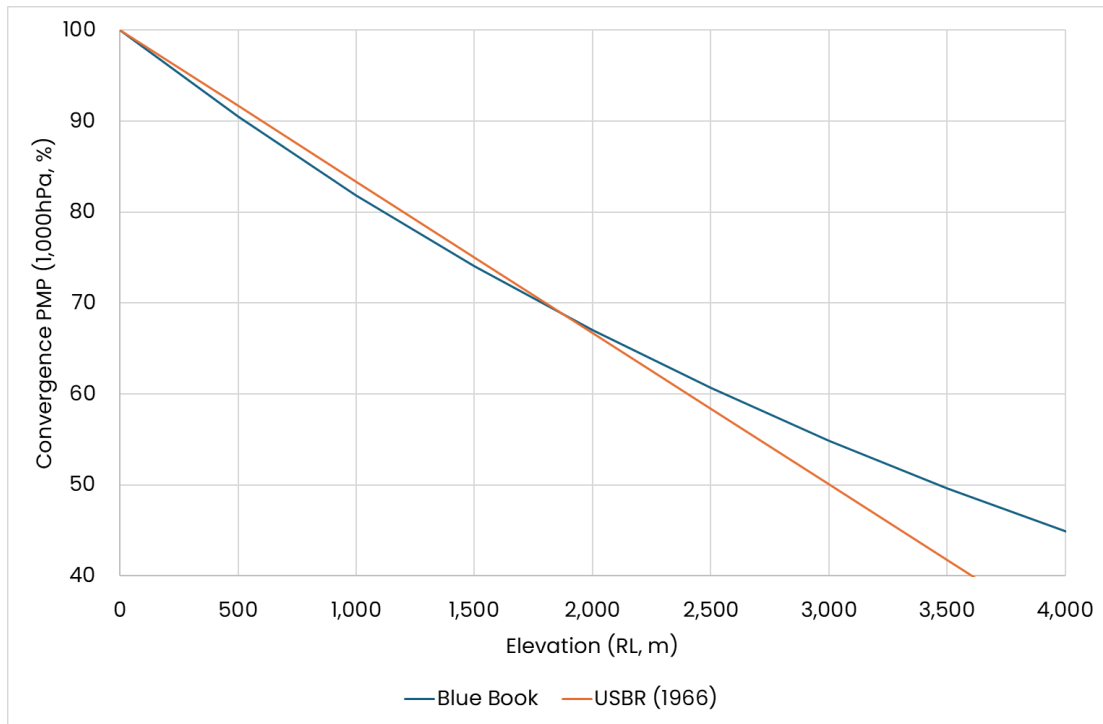


Figure 41: Decrease in convergence PMP with elevation as implemented in the Blue Book and as specified by the United States Weather Bureau (USBR).

MVP

We have implemented the same adjustment for elevation as recommended in the Blue Book. We note that WMO (2009) and subsequent studies have implemented greatly improved methods to adjust for moisture barriers and elevation. We recommend that future studies improve this adjustment based on the more recent methods.

4.6 Depth-area reduction factors

Blue Book

The Blue Book presents sets of depth-area reduction factors for each of the three differentiated storm transposition regions, which are solely dependent on catchment area. The Blue Book derived these factors as typical values at 24-hour duration from the 20 largest events in their storm catalogue. We note that the Blue Book storm catalogue was compiled on a 10km grid (100km² resolution) with a bi-cubic spline interpolation then being used to reduce the grid to 5km (to provide precipitation estimates for 25km² areas).

MVP

HIRDS presents nation-wide depth-area reduction factors for non-mountainous areas of New Zealand, with additional dependency on storm duration. The factors were derived generally from annual maximum storms (as recorded at individual gauge locations) between 1-hour and 120-hour durations, over 10km² to 500km² areas. HIRDS also provides more refined equations for specific locations (Auckland, Christchurch and Tasman), and an option to include dependence on return period. It does not, however, define what areas are mountainous (or

non-mountainous). We considered implementing the HIRDS-based national depth-area reduction factors for both mountainous and non-mountainous areas in the web-app as:

$$ARF = 1 - 0.024 \times A^{0.41} \times D^{-0.53} \quad (21)$$

where ARF is the reduction factor, A is the area in km^2 , and D is the duration in hours.

Depth-area curves from storms in the Blue Book storm catalogue (coloured lines) are compared with the single depth-area reduction curve for the selected region provided in the Blue Book (black line), and the curve calculated using HIRDS (red; equation 21) in Figures 42, 43 and 44.

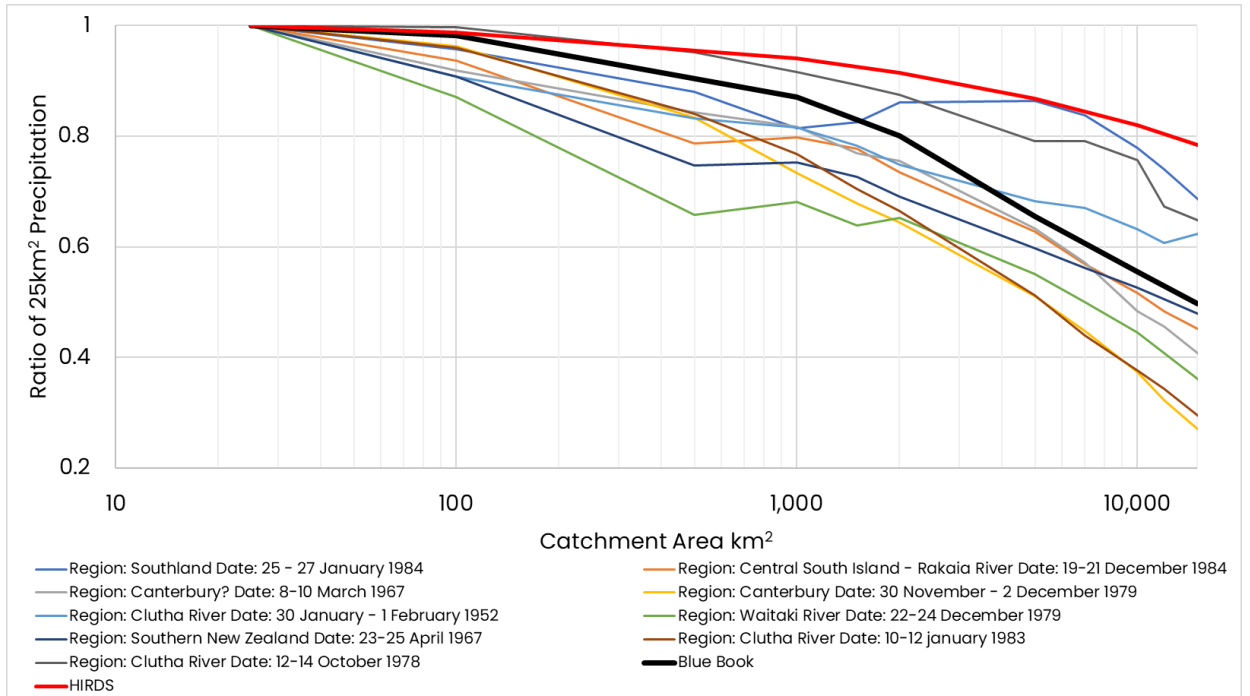


Figure 42: Depth-area reduction factors for the south-east of the South Island as provided by the Blue Book (black line), the analytical relationship from HIRDS (red line), and for 9 storms selected from the Blue Book storm catalogue.

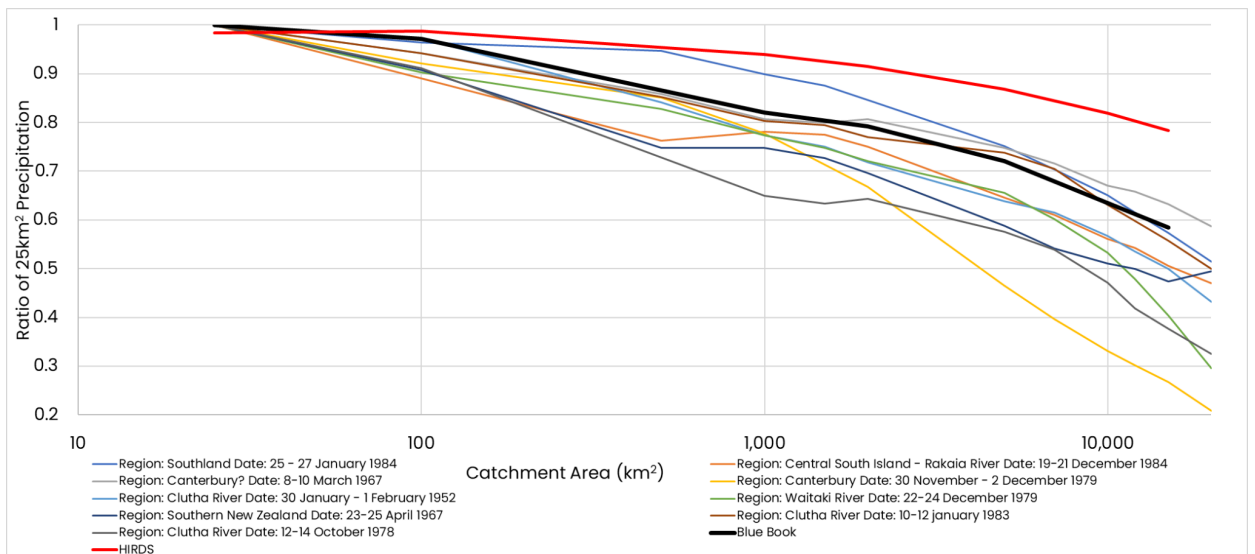


Figure 43: As for Figure 42 but for the South Island alpine region.

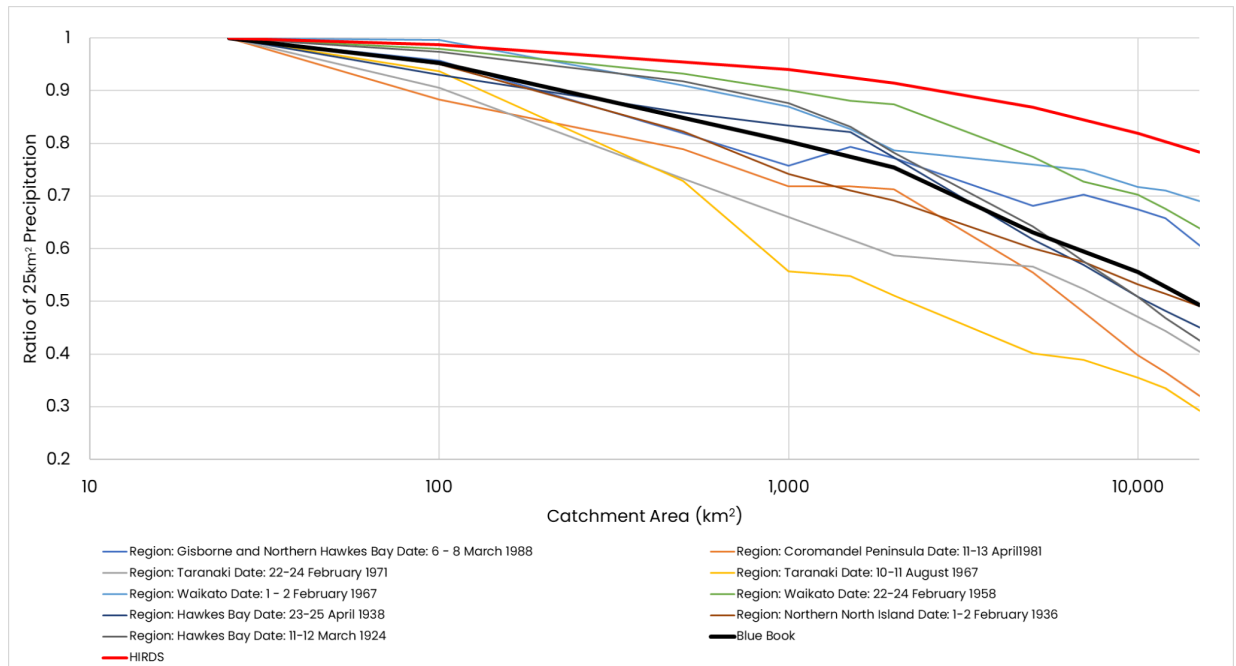


Figure 44: As for Figure 42 but for the North Island.

The HIRDS depth-area curves appear as an upper limit on the curves from the Blue Book storm catalogue and are generally much more conservative for large area storms than the Blue Book curves. The HIRDS curves are overly conservative compared to the Blue Book curves for catchments larger than 500km² in the South Island Alpine and North Island regions. We therefore considered the HIRDS depth-area reduction curves to be too conservative if applied as a depth-area reduction factor for a PMP type storm.

To provide further context for the Blue Book depth-area reduction curves, we have selected storms from our updated storm catalogue with:

1. The three largest $C_{\max}/C_{100}$ ratios.
2. The three highest $C_{\max}$ estimates over a 100km² area and a 20000km² area.

We consider that these are most likely to be representative of high efficiency events, which may be most similar to PMP type events. The depth-area reduction curves from these storms are compared with similar curves from HIRDS, the Blue Book, and a ratio of GEV estimates of the $C_{\max}/C_{100}$ ratio at 10-year ARI derived from our updated storm catalogue for each of the 11 index areas (see Figures 45, 46 and 47). These figures provided confidence that the Blue Book curves remain appropriate for implementation in the web-app. If index PMP maps were derived for each considered storm area (nationally), this would be the effective reduction expected for any deviations from a 100km² index area. We recommend that future studies consider deriving index PMP estimates for different index areas to remove the need for a depth-area modifier. We note that both the Blue Book and the improved depth-area curves were derived at a single 24-hour storm duration, and this is the same approach which we have followed. We recommend that future studies consider how the depth-area curves might differ for other storm durations.

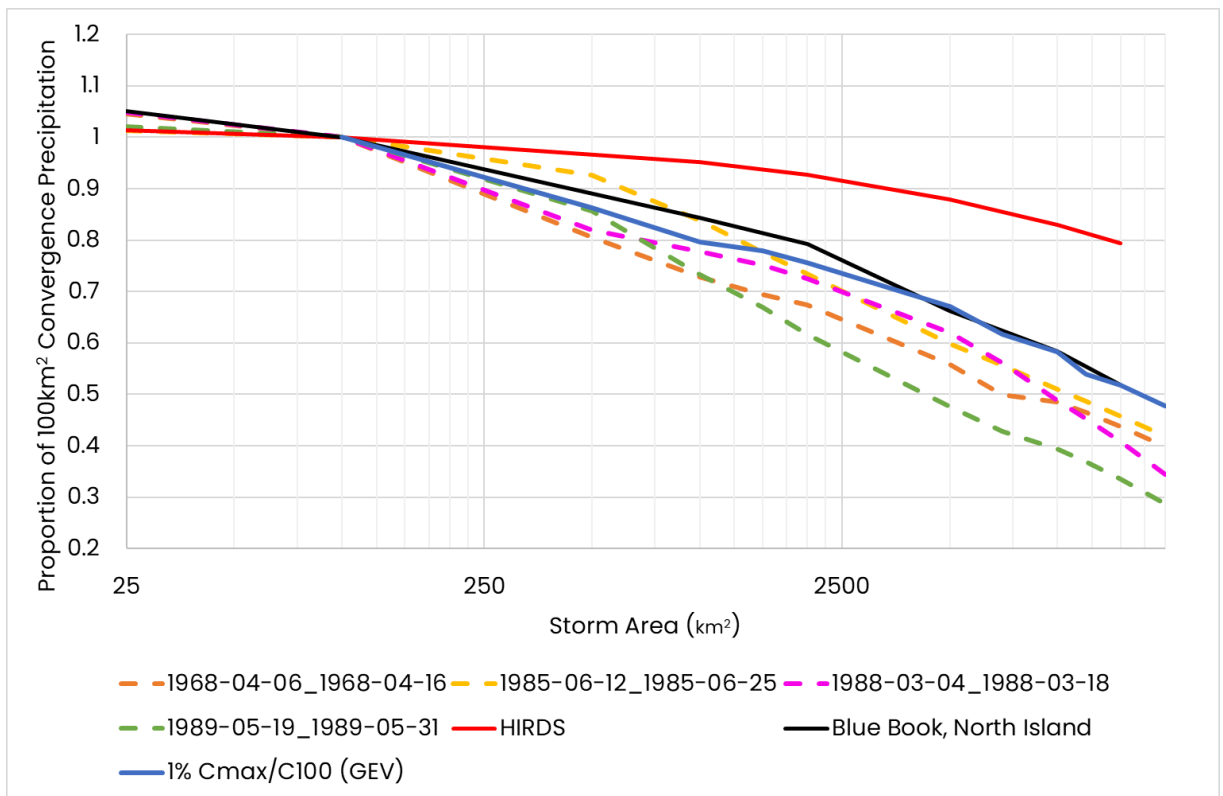


Figure 45: Depth-area reduction curves for the North Island region.

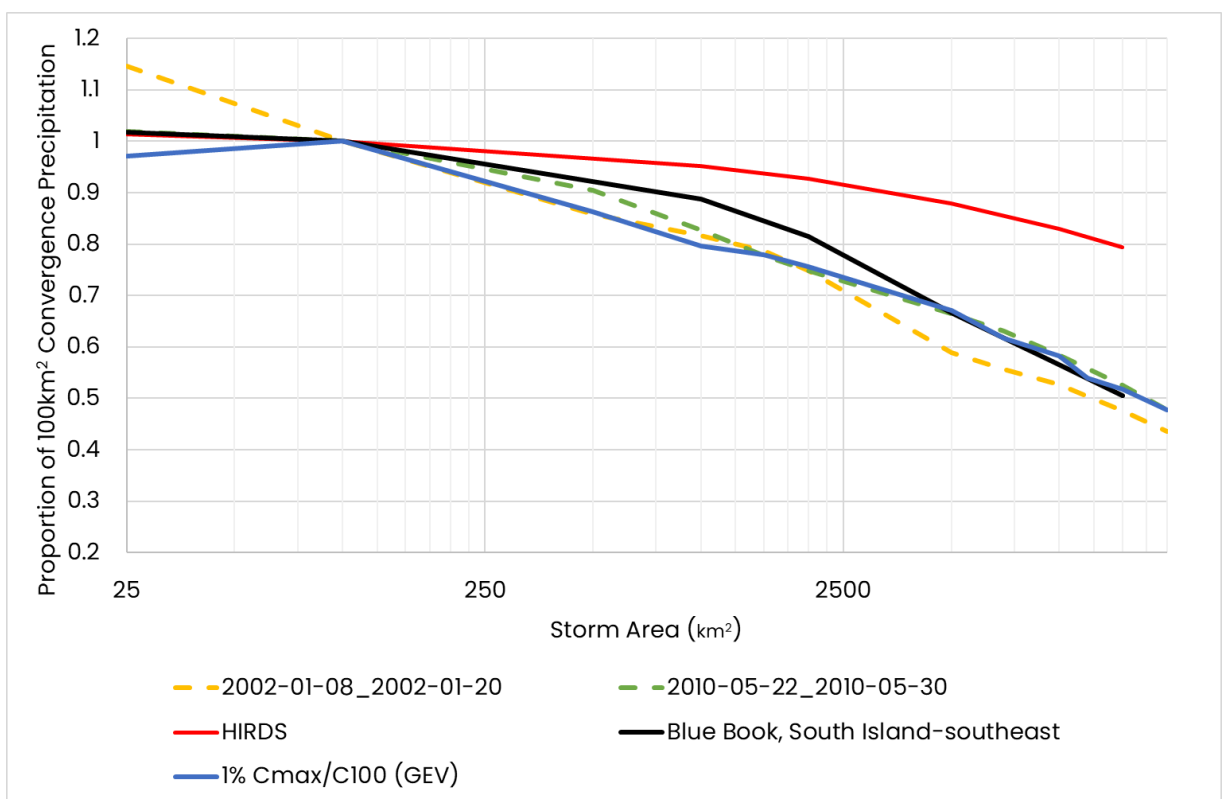


Figure 46: Depth-area reduction curves for the South Island south-east region.

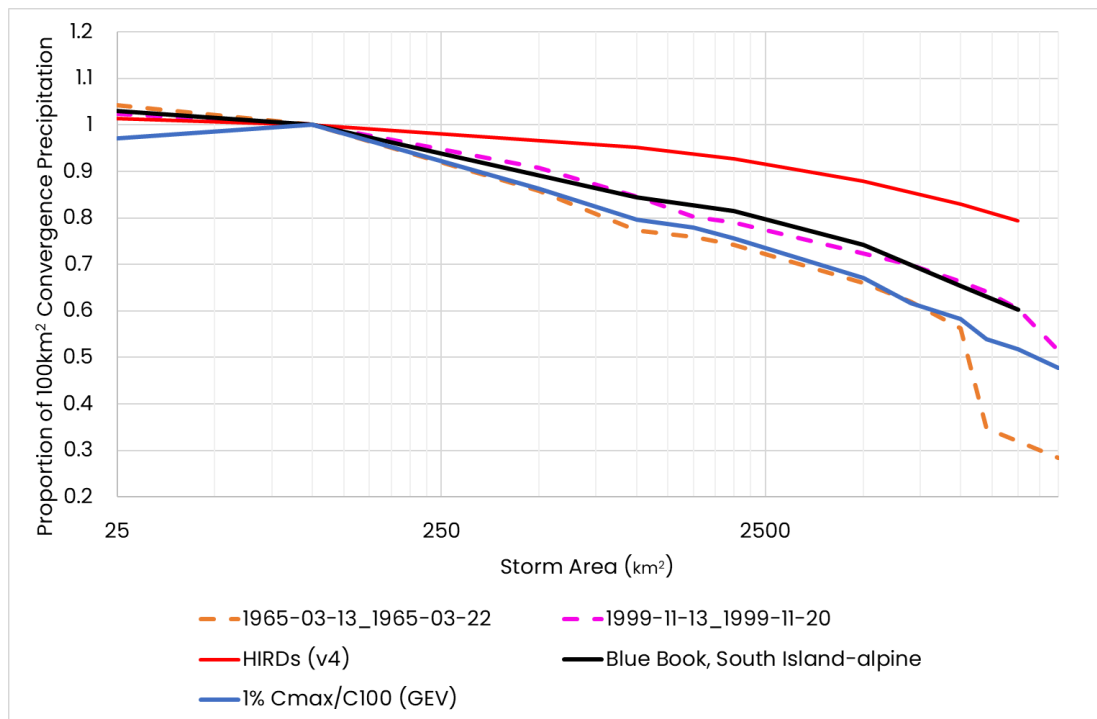


Figure 47: Depth-area reduction curves for the South Island Alpine region.

4.7 Depth Duration Ratios

Blue Book

Tomlinson and Thompson (1992), and Thompson and Tomlinson (1995) present a map of 12/24 hour duration ratios recommended for storms covering large areas and long durations. Ratios were developed from:

- i. Storm ratios extracted from the extreme storm catalogue.
- ii. Ratios from events with an ARI of 200 years computed from autographic precipitation gauges (following a similar procedure to Tomlinson (1980), a precursor to HIRDS v1).
- iii. Ratios determined from maximum recorded precipitation values from autographic precipitation gauges.

MVP

We considered calculating the same depth-duration ratios but using the HIRDS data set and an ARI of 250 years (Figure 48). The HIRDS 12/24 hour ratio appeared to have greater spatial variability than the map presented in the Blue Book. This is likely a result of:

- Differences in spatial resolution - approximately 250m resolution in HIRDS compared to the 10km resolution in the blue book.
- Additional precipitation data available for interpretation.

Depth-duration ratios derived from HIRDS are somewhat dependent on ARI. The magnitude of this variance tends to be lowest in Northland and greatest in the southern Hawkes Bay and the South Island-southeast - see Figure 49 which shows the percentage differences in 12/24-hour depth-duration ratios between an ARI of 250 years and an ARI of 50 years. We note that the dependence of depth-duration ratios on ARI was not considered in the Blue Book methodology.

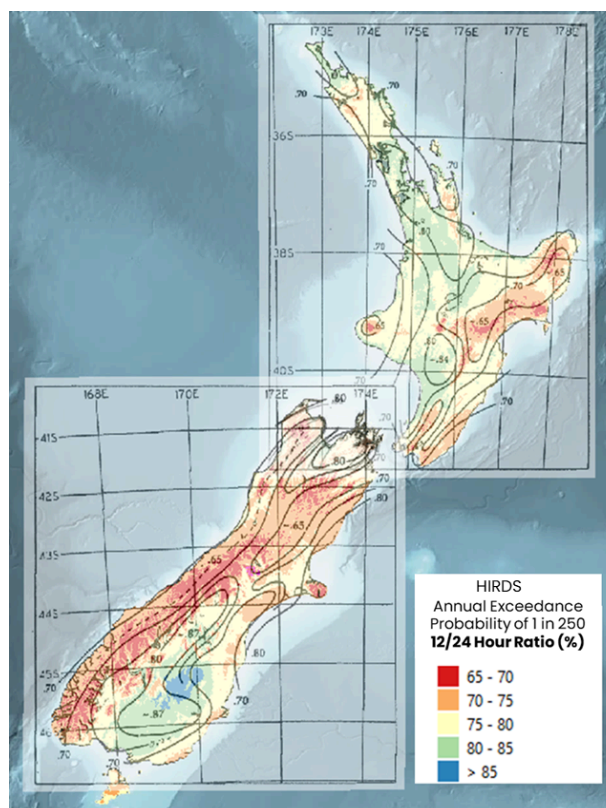


Figure 48: 12/24-hour depth-duration ratios from HIRDS (coloured cells) overlaid on the equivalent map extracted from the Blue Book (their Figure 7.19)

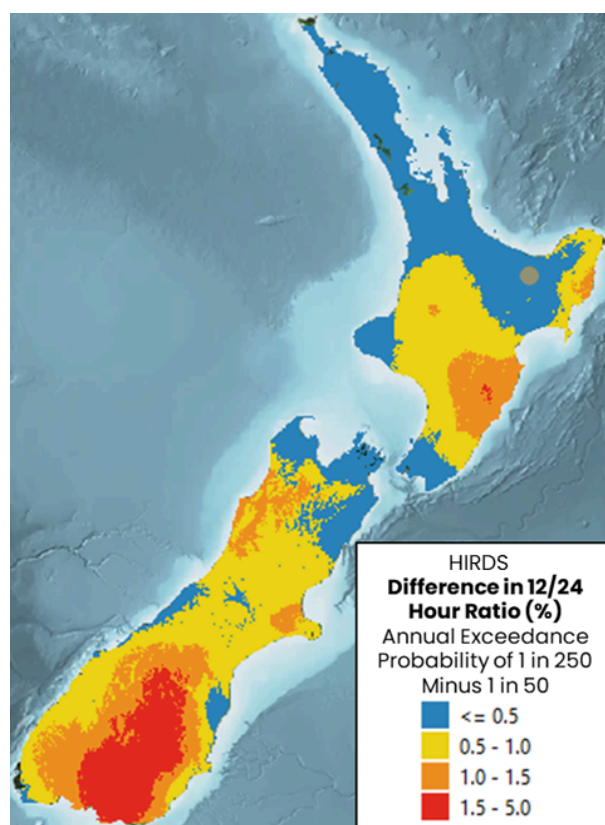


Figure 49: The percentage difference between 12/24-hour depth-duration ratios at ARIs of 250 years and 50 years, as derived from HIRDS.

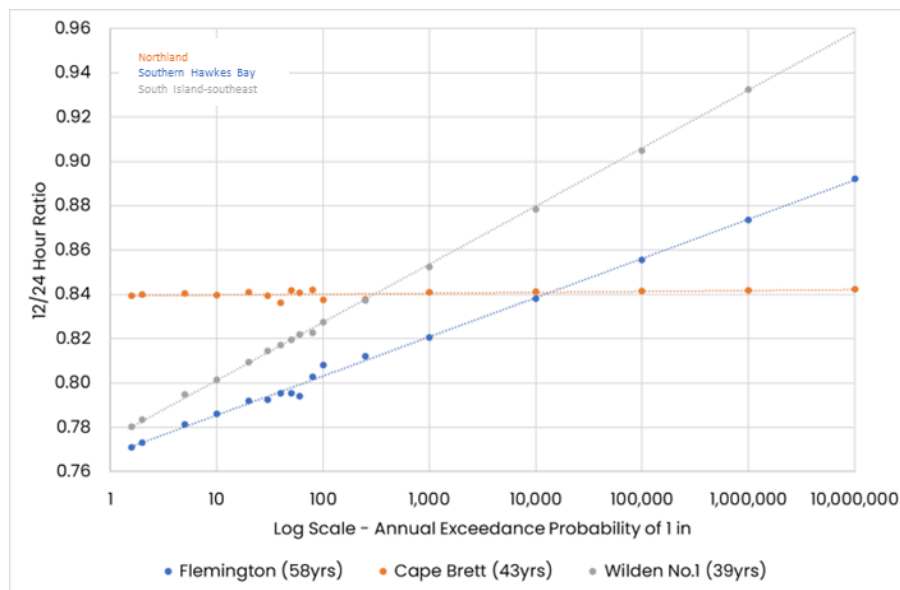


Figure 50: 12-hour/24-hour depth-duration ratios for three arbitrarily selected gauges in Northland, Southern Hawkes Bay, and the South Island-southeast as derived from HIRDS.

As can be seen from Figure 50, over the South Island there is a clear dependence of the 12/24 depth-duration ratio with ARI. We therefore suggest that the depth-duration ratio at an ARI of 250 years may not be representative in all regions of New Zealand for events with an ARI significantly greater than 250 years (i.e. a PMP type event). Given this potential dependence on ARI, we have not applied depth-duration factors in the MVP but rather note that the derivation of duration-specific index PMP maps (Section 4.3.4) circumvents the need for such factors.

4.8 Depth duration adjustments

Blue Book

Tomlinson and Thompson (1992), and Thompson and Tomlinson (1995) present a figure and table which uses the 12/24-hour depth-duration ratio to extrapolate a 24-hour catchment average PMP to other storm durations between 12 and 96 hours. Tomlinson and Thompson (1992) recommended that storms for small areas and short durations are calculated using a 6/1-hour ratio of 2.1, making no allowance for the orography in which the storm occurs. This recommendation was later superseded by Thompson and Tomlinson (1993), who present a range of 6/1-hour ratios and recommend that the relevant ratio for a given site/orography is selected based on storm data. A table of adjustments for durations between 30 minutes and 6 hours (based on the selected 6/1-hour ratio) was provided.

MVP

Depth-duration ratios at 250-year ARI were extracted at precipitation gauge locations in HIRDS. The resulting 12/24-hour ratios varied from 0.65 to just under 0.9. Figure 51 presents results where the 12/24-hour ratios were close to 0.7 and 0.8 respectively, and compares them with the corresponding curves from the Blue Book.

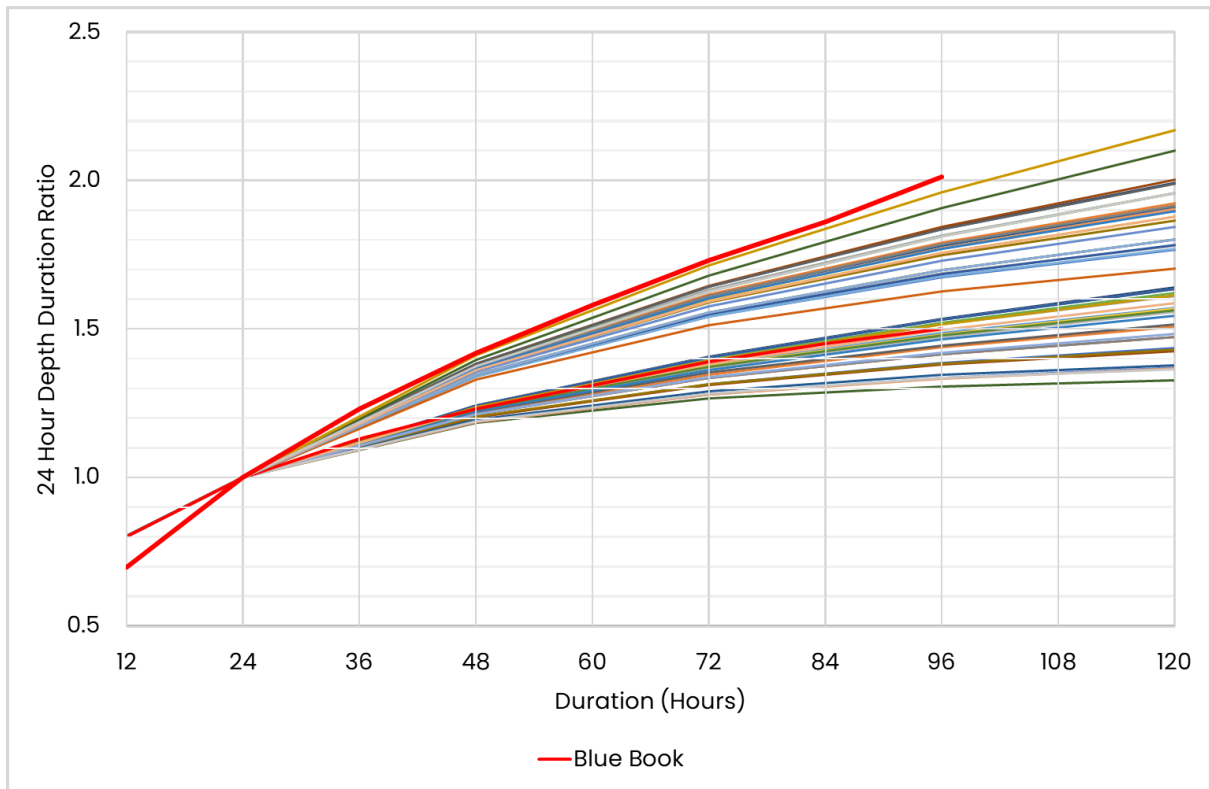


Figure 51: Comparison of HIRDS and Blue Book depth-duration ratios.

Gauges with a 12/24-hour ratio of 0.7 had a 96/24-hour ratio which was 5% to 40% lower than that presented in the Blue Book. Gauges with a 12/24-hour ratio of 0.8 had a 96/24-hour ratio which was between 5% higher and 20% lower than that derived in the blue book. We conclude that the ratios in the Blue Book appear to have been generally derived in a conservative manner when compared to the HIRDS ratios. Because we have derived index PMP fields separately for each precipitation duration (see Section 4.3.4), this circumvents the need for using such depth duration adjustments.

4.9 Temporal pattern

Blue Book

The Blue Book derives temporal patterns to indicate a possible temporal cadence of precipitation across the duration of the storm which is essential for hydrological modelling based on the PMP estimate. It notes that while there is a wide variety in the temporal distributions of precipitation within a storm, severe storms tend to exhibit a single peak intensity. Temporal patterns of precipitation intensities within storms were derived using a method of average variability (Pilgrim et al., 1969, 1975), whereby:

1. Each burst within a storm is divided into a number of sub-periods (in this case these were hourly time increments).
2. The maximum intensity occurring within the time period associated with a PMP estimate is assumed to be equal to the average of the sub-period maximum intensities.
3. Other lesser precipitation intensities are derived by the same method.

For the large areas and long durations method, temporal patterns were differentiated for the North and South island from storms as follows:

- **North Island:** A single storm, Cyclone Bola (March, 1988)
- **South Island:** Four storms, October 1978, November/December 1979, January 1984 and December 1984.

Derived intensities were then arranged in a 'most likely sequence', taking into account the temporal location of the maximum or peak storm intensity across a wider set of storms (Figure 52). The wider set of storms included those with more than 175mm of precipitation (recorded at a given gauge) over a 3-day period (relaxed to 100mm east of the South Island main divide). This included 80 storm events in the North Island, and 329 storm events in the South Island. From this information, smoothed patterns were developed using a simple intensity-duration relationship. For the small areas and short durations method, a single temporal pattern was originally derived from a February 1966 (typo in Blue Book, which stated 1976) storm in Northland, and a December 1976 storm in Wellington. However the aforementioned temporal pattern was not included in the later Thompson and Tomlinson (1993) study which, instead, presented a series of hourly increments which varied with a 6/1-hour ratio. Thompson and Tomlinson (1993) does not state exactly which storms these hourly increments were derived from.

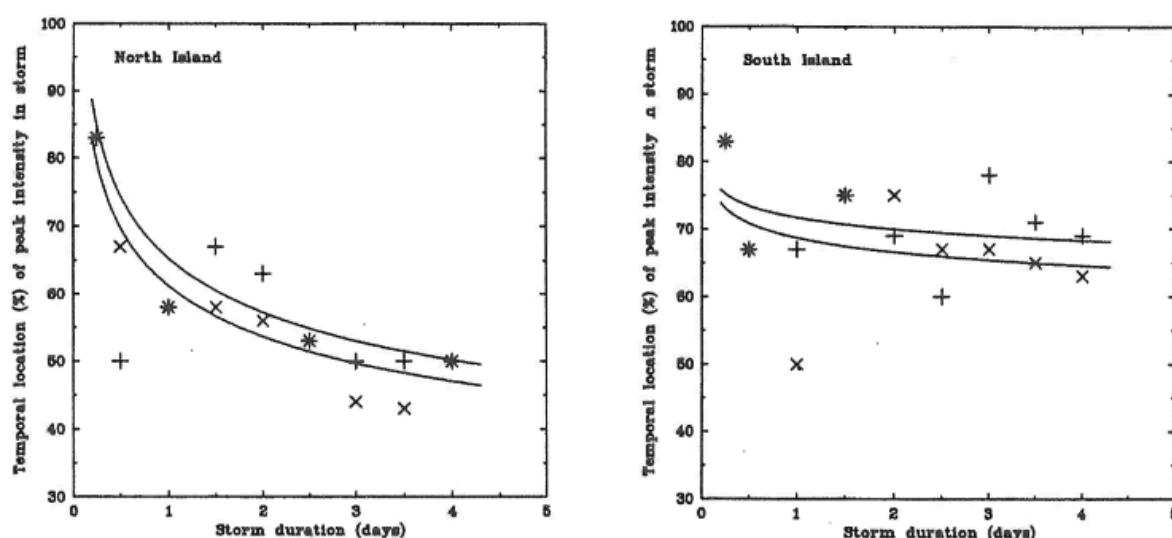


Figure 52: Timing of the peak precipitation intensity - Figure 7.21 of the Blue Book.

MVP

HIRDS applied the same method of average variability, although it used this to both define intensities and to arrange them in sequence. It considered temporal patterns from annual maximum storms (recorded prior to 2016) from approximately 70 sub-hourly precipitation gauges. We have selected not to use the HIRDS temporal pattern for defining the hour-by-hour precipitation intensity through a PMP event since the annual maximum storms considered by HIRDS are expected to have higher peak intensities than more PMP-type severe events. Rather, we considered updating intensities using the Blue Book temporal pattern, considering the three storms with the highest C_{100} and C_{max}/C_{100} ratios in our updated storm catalogue, taking into

account the same Pilgrim and Cordery (1975) method of average variability, and using the same sequence of peak intensities as in the Blue Book. Results are compared to the Blue Book temporal patterns at 24-hour duration in Figure 53 for storms of 1000km² area and in Figure 54 for storms of 100km² area. Because the patterns appear to be very similar, we have not recommended improved temporal patterns beyond those developed in the Blue Book.

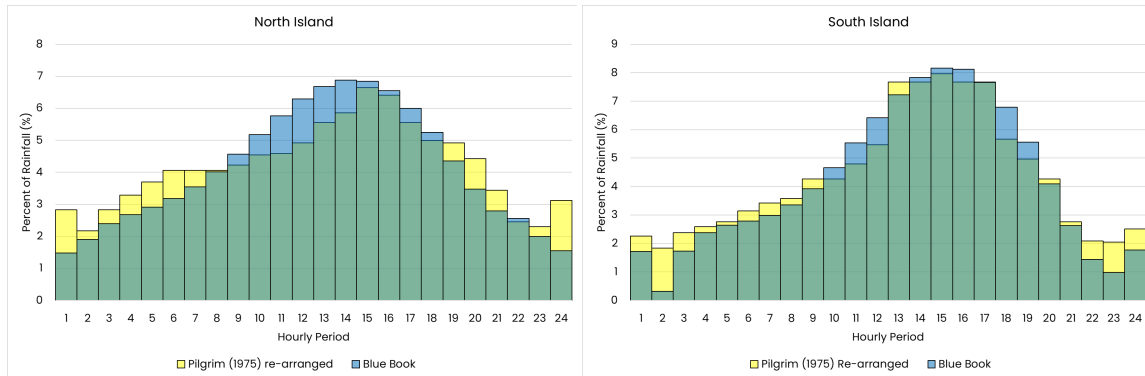


Figure 53: The 24-hour temporal pattern for a 1000km² area storm for (left) the North Island and (right) the South Island. Values from the Blue Book are shown in blue while values from our application of the same method (used in the Blue Book) to storms from our catalogue are shown in yellow - regions of coincidence therefore appear green.

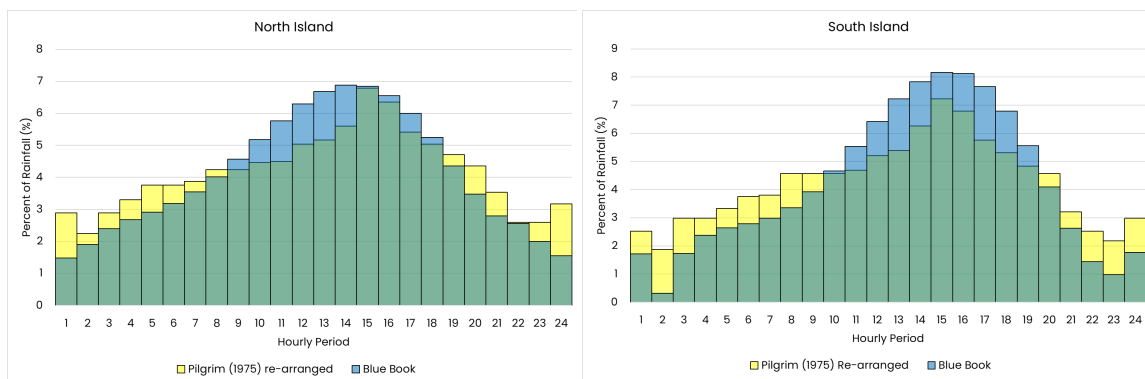


Figure 54: The 24-hour temporal pattern for a 100km² area storm for (left) the North Island and (right) the South Island. Values from the Blue Book are shown in blue while values from our application of the same method as used in the Blue Book to storms from our catalogue are shown in yellow - regions of coincidence therefore appear green.

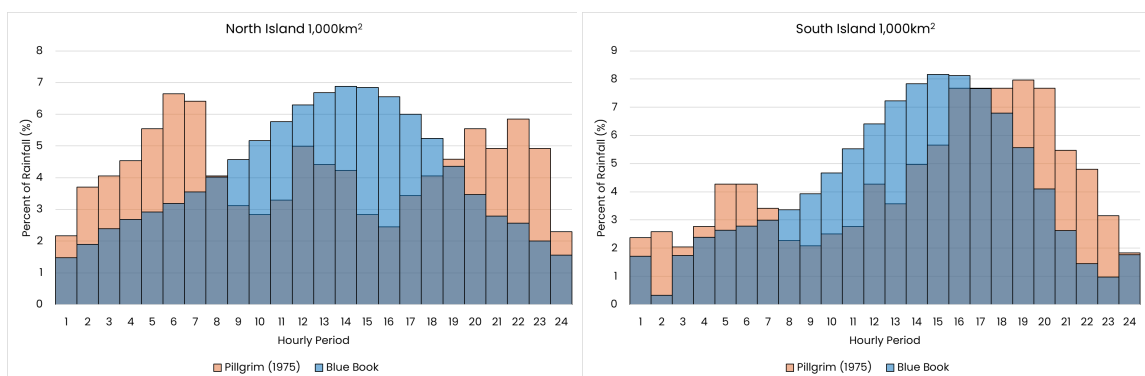


Figure 55: Comparison of the Pilgrim and Cordery (1975) temporal sequence of intensities (orange) and the 'most likely sequence' used by the Blue Book (blue) for the North Island (left) and the South Island (right).

We do, however, wish to highlight two areas of potential uncertainty in the Blue Book temporal patterns:

1. The selected 'most likely sequence' derived in the Blue Book produces considerably different results to the sequence derived from Pilgrim and Cordery (1975, Figure 55). The largest storms in the storm catalogue all appear to have multiple peaks, whereas the selected most likely sequence only has a single peak.
2. The selected burst within storms was derived from the period which gives the highest total over the duration of interest. This was not necessarily a complete burst; often intensities were high in the period preceding and following the burst. As such, when compared to storms where the length of the burst was equal to the duration of interest, higher proportions of precipitation occurred in the first and last periods, and lower proportions of precipitation occurred in peak periods.

We recommend that future studies consider creating alternative, or additional, temporal patterns including:

1. Front and back weighted temporal patterns, with multiple peaks.
2. Larger and smaller area storms.
3. Differentiation by storm transposition regions.
4. A nested pattern.

Note of caution

When using the aforementioned temporal patterns to assess a Probable Maximum Flood, it is important to bear in mind that the temporal patterns cover a single intense burst within the storm. For the majority of storms which these were derived from, there was considerable precipitation prior to and/or following this burst. There is no reason why this would not also be the case within a Probable Maximum Storm. This should be accounted for when selecting precipitation loss parameters associated with a Probable Maximum Flood.

4.10 Spatial pattern

The Blue Book large areas and long durations methodology provides an average PMP over the area of the catchment. It does not include a spatial pattern. This presents challenges for estimating a Probable Maximum Storm (PMS) or a Probable Maximum Flood (PMF) using the Blue Book-derived PMP. Practitioners in New Zealand have tended to apply a spatial pattern using either:

- a) The index PMP pattern - which is generally thought to produce overly conservative results as it typically represents depth-area-duration results from several storms and therefore the pattern may not be realistic for any single storm. However, this is generally not the case as practitioners applying this pattern tend to preserve the magnitude of the catchment average PMP. As such, the PMS depths are probably overestimated in some areas of catchments and underestimated in others.
- b) The pattern of estimated mean annual, or 100-year ARI, precipitation (or similar) - which, similar to (a), is not necessarily related to a single storm and is likely to

overestimate PMS depths in some areas of the catchment and underestimate them in others.

- c) An observed storm pattern (from within the catchment) - which, while it is related to a single storm, is unlikely to reflect the PMS pattern as it does not consider storm transposition or maximisation processes which are intrinsic to the PMP analysis. Again, this is likely to result in an overestimate of PMS depths in some areas of the catchment and an underestimate in others.

These limitations are unlikely to be resolvable without implementing an alternative methodology. An alternative generalised methodology (e.g., the latest methodology employed in Canada and British Columbia), could allow selection of a PMS from maximised and transposed observed storms, such that the PMS and associated spatial and temporal patterns can be determined from the PMP storm catalogue.

5. Accounting for the effects of climate change

5.1 Blue Book

The Blue Book acknowledged that climate change would likely increase the moisture holding capacity of the atmosphere near the surface which, in turn, would likely increase the intensities of convective precipitation (i.e., increase PMP estimates). It suggested that an increase in 100-year ARI 12-hour maximum persisting dew point temperature of 1°C would lead to an increase in PMP of about 7%, noting that the IPCC had forecast an increase in the global mean surface temperature anomaly of 1.5°C to 4.5°C. The Blue Book also considered results from a global climate model (CSIRO4) developed by the Division of Atmospheric Research (CSIRO, Melbourne). This identified an increase in extreme precipitation (for unspecified ARIs) of about 11% over Australia; it was suggested that at New Zealand latitudes there might be a smaller effect. However, no guidance was provided on how to extrapolate this to a PMP estimate.

5.2 MVP: Clausius Clapeyron relationship

We considered simply applying the Clausius-Clapeyron relationship, i.e., a 7% increase in moisture carrying capacity of the atmosphere per 1°C warming, as a post-hoc scaling of the PMP for a given degree of global warming. This would essentially follow the recommendation of the Blue Book. However the HIRDS technical report (Carey-Smith et al., 2018) highlights that the application of such a relationship is unlikely to be appropriate for many regions of New Zealand and for many precipitation durations.

5.3 MVP: Post-hoc scaling of the PMP

Rather than naively using a Clausius Clapeyron relationship, we considered results from five different data sets that give some indication as to how precipitation over New Zealand either has changed, or is expected to change, under the effects of a warming climate. Three of these sensitivity fields resulted from analysis of (i) the nn-GEV, (ii) weather@home, and (iii) CCAM data sets described in Section 4.4.2. Added to these were:

1. The **CMIP5-RCM** sensitivity fields underlying the HIRDS recommendations on how to modify precipitation extremes to account for climate change. Sensitivities were derived from simulations generated using a regional climate model over New Zealand, driven by sea surface temperatures from six global climate models which were selected from the IPCC 5th assessment report as the models that simulated New Zealand's observed climate history best (Ministry for the Environment, 2018). It is important to note, however, that because of the variability between the six derived fields, a single value to be applied across all of New Zealand was recommended in HIRDS.
2. Sensitivity fields derived from the **CAM5.3** model made available through the FEWhANZ2 project of the Deep South National Science challenge. Simulations were available over five epochs: (1) an ensemble of 5 simulations covering pre-industrial conditions, (2) an ensemble of 5 simulations covering present day conditions (1996 to 2015), (3) an ensemble of 6 simulations under 1.5°C of global warming, (4) an ensemble of 6 simulations under 2.0°C of global warming, and (5) an ensemble of 6 simulations under 3.0°C of global warming.

One of the challenges in using the sensitivity fields derived from these five data sets is that the sensitivities were derived with respect to three different temperature covariates: the CMIP5-RCM sensitivities are with respect to a New Zealand land surface temperature anomaly, the nn-GEV sensitivities are with respect to a global mean surface temperature anomaly, and the weather@home, CAM5.3 and CCAM sensitivities are with respect to a southern-hemisphere land surface temperature anomaly. We have used linear fits to ERA5 spatially averaged monthly mean temperature estimates to derive relationships between these different temperature covariates (Figure 56).

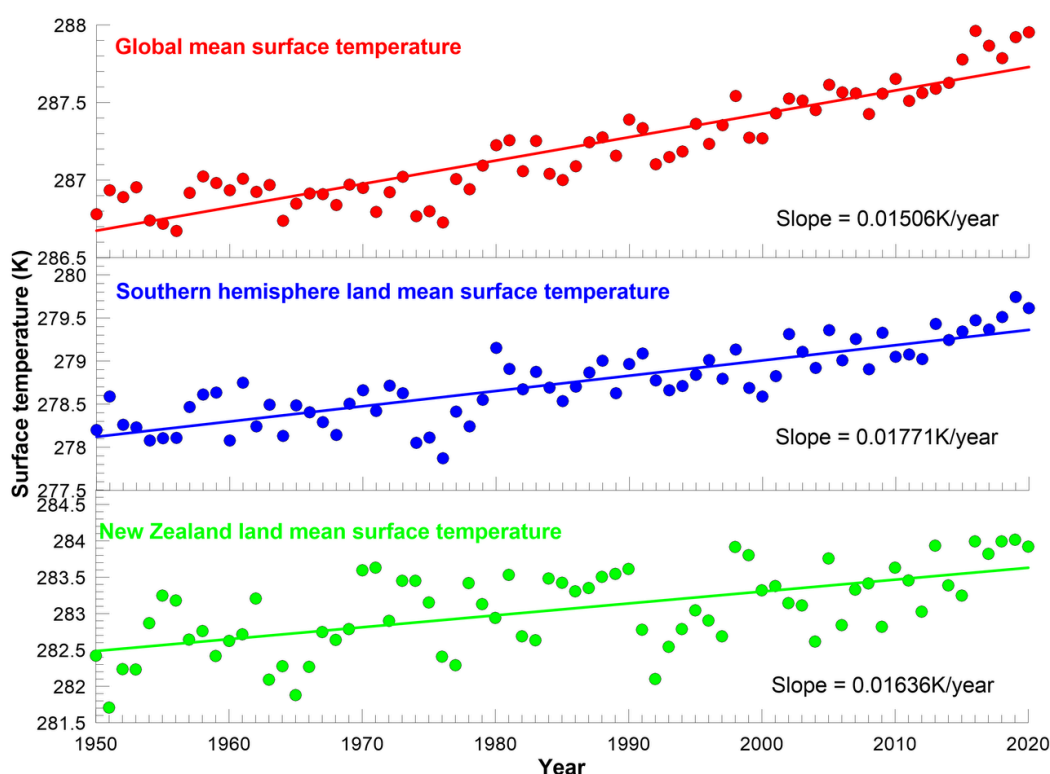


Figure 56: Trends in three different temperature data sets derived from the ERA5 reanalysis (see Section 4.4.1)

This suggests the following factors to adjust data sets to refer to sensitivities against a common covariate of global mean surface temperature:

- An adjustment of 8.6% ($0.1636/0.1506$) per degree of New Zealand land surface temperature anomaly.
- An adjustment of 17.6% ($0.01771/0.01506$) per degree of Southern Hemisphere land surface temperature anomaly.

Sensitivities at an ARI of 100 years were investigated under the assumption that such storms are probably already near maximum efficiency and thus percentage changes in moisture are likely to be similar; we note that the HIRDS sensitivities (Figure 57) appear to approach an asymptote at the higher ARIs.

The advantages and disadvantages of each of the five resultant sensitivity maps, shown in Figure 58, were then considered to derive an expert-judgement weighting for each field.

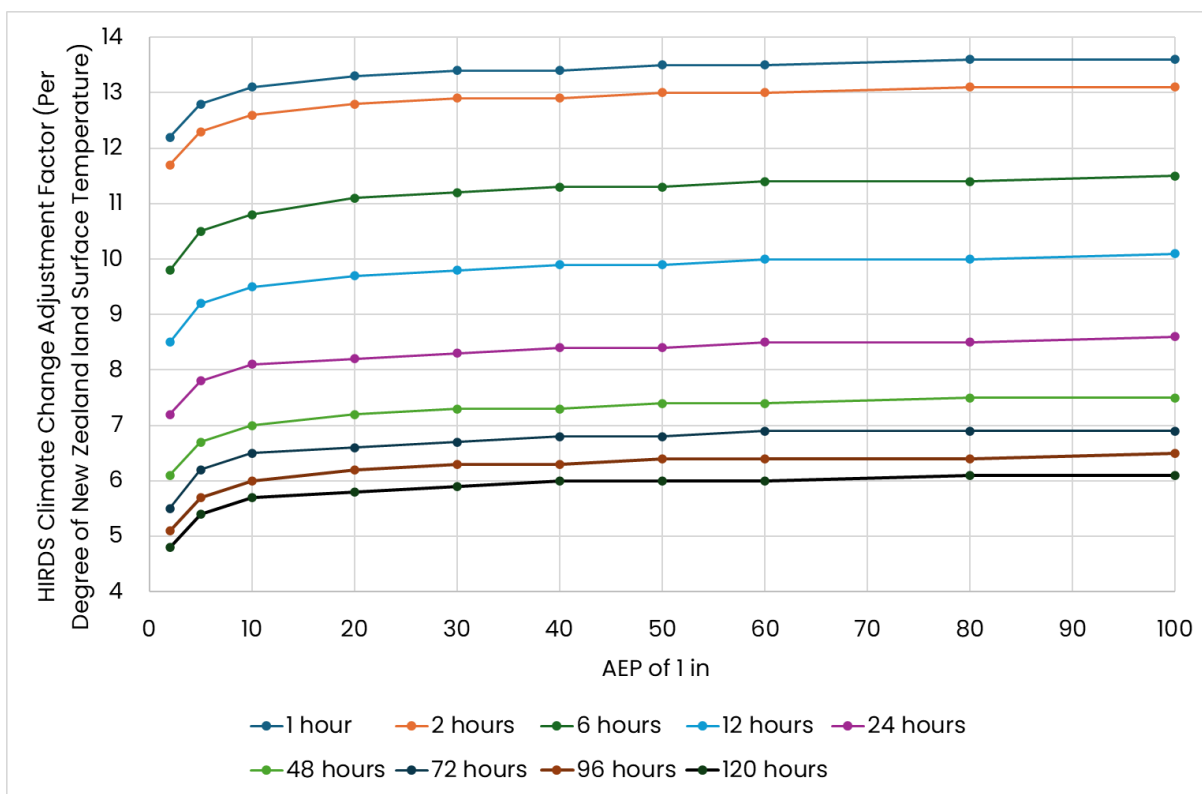


Figure 57: Extreme precipitation sensitivities to warming of the New Zealand land surface as a function of ARI and precipitation duration, as extracted from HIRDS.

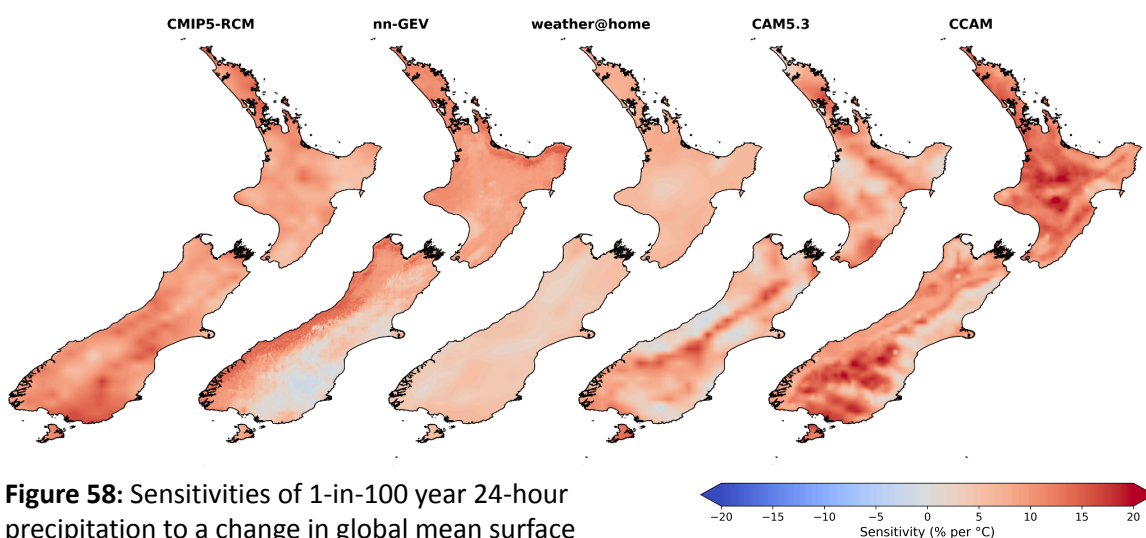
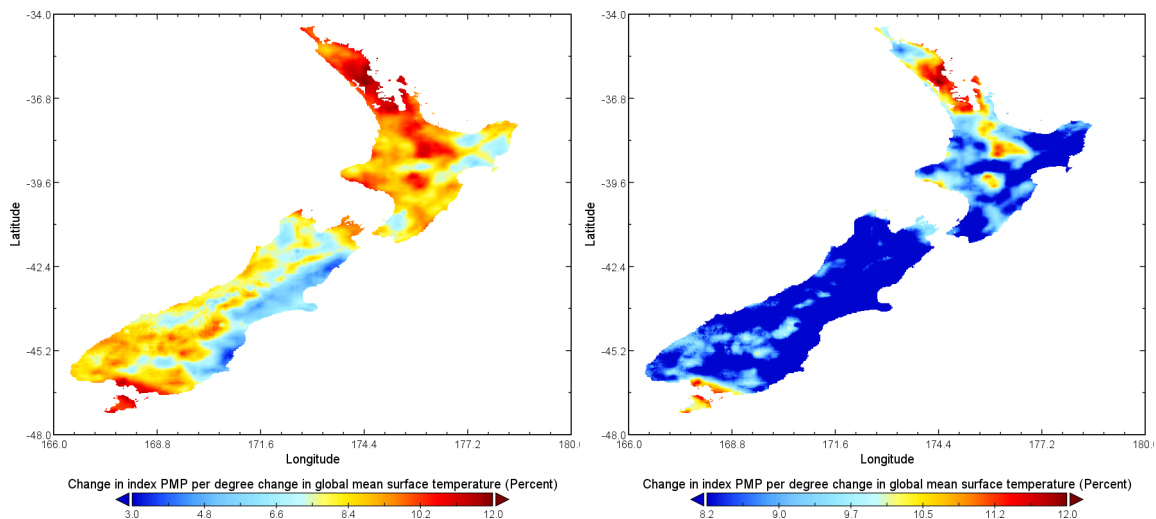


Figure 58: Sensitivities of 1-in-100 year 24-hour precipitation to a change in global mean surface temperature anomaly.

The resultant weightings, and the reasoning behind each weighting, are summarised in Table 7. The weighted average of the five data sets (using the weightings listed in Table 7) is shown in the leftmost panel of Figure 59. Given that some values were unexpectedly low (e.g., along the east coast of the South Island), it was decided to replace all values lower than the mean (8.2%) with the mean. This is to derive a conservatively safer estimate of the sensitivity of extreme precipitation to climate change. The resulting field is shown in the rightmost panel of Figure 59.

Table 7: Precipitation sensitivity data set weightings

<i>Data set</i>	<i>Weighting</i>	<i>Reasoning</i>
CMIP5-RCM	25%	Fairly large volume of data. This data set is the basis for HIRDS that a lot of practitioners use.
nn-GEV	15%	Has the advantage of being published in the peer-reviewed literature. However, it is retrospective and says nothing about what will happen in the future. Very high spatial resolution (1.5km), but detail does not equal quality.
weather@home	22.5%	Statistically robust and with values close to the Clausius Clapeyron expectation value of 7%.
CAM5.3	15%	Fairly large spatial variability.
CCAM	22.5%	This is going to be the 'official' model for MfE-sanctioned New Zealand climate projections. However, it shows sensitivities somewhat higher than most of the other fields.

**Figure 59:** (left) The weighted sensitivity map. (right) The weighted sensitivity map once all values below the mean were replaced by the mean.

The mean value of that modified field is 8.8% which, when scaled to a temperature covariate of New Zealand land surface temperature anomaly, equates to a value of 8.1% which is similar to the 8.6% applied in HIRDS. While the same process could have been applied to durations other than 24-hour, many of the data sets used here only provide data at daily resolution. Therefore, we have selected to scale the field to provide sensitivities for alternative duration storms using the HIRDS 100-year ARI factors listed in Table 8. The drawback of this approach is that it assumes that the selected spatial pattern of changes in factors will be similar for storms of different duration, which is unlikely to be the case where the type of storm causing an extreme event changes. We have fitted a log-linear trendline to estimate factors for durations not presented in HIRDS.

Table 8: Factors used to scale the field shown in the rightmost panel of Figure 59 to generate sensitivity fields for durations other than 24 hours.

<i>Duration (hours)</i>	<i>HIRDS sensitivity (%)</i>	<i>Scaling w.r.t. 24-hour sensitivity</i>
1	13.6	1.58
2	13.1	1.52
3	-	1.42*
6	11.4	1.34
12	10.0	1.17
24	8.5	1.00
36	-	0.94*
48	7.5	0.87
72	6.9	0.80
96	6.5	0.76
120	6.1	0.71
168	-	0.65*

*Approximated from a log-linear fit.

5.4 Future work

We recommend that in future work, sensitivities to a climate covariate are derived individually for the several terms that comprise the PMP estimate, rather than applying a single post-hoc correction to the index PMP. This is likely to result in a more nuanced assessment of the effects of climate change on the different processes underlying the generation of PMP values. Research foci to understand the effects of climate change within the following areas would be required:

1. The types of storms which could generate a PMP.
2. The regions which different types of storms could affect (transposition regions).
3. The maximum dew point temperatures.
4. Total precipitation (T_{100}) at the various index durations.
5. Convergence only precipitation (C_{100}) at the various index durations.
6. Storm maximisation which would require consideration of:
 - a. How the dew point temperature during events in the storm catalogue might vary.
 - b. How precipitation fields in the storm catalogue may also have varied.
 - c. Whether event specific storm dynamics may have been altered.
7. Depth-area reduction factors
8. Temporal pattern(s), including as a result the storm intensification factor.
9. Spatial pattern(s)

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Appendix A - Total precipitation - storm verification

General

The following figures include:

1. Georeferenced storm isohyets extracted from the Blue Book.
2. Precipitation gauge totals, for the same period, from gauge data hosted in the National Climate Database which recorded throughout the full period of the event.
3. Gauge-corrected ERA5 total precipitation estimates for the same period.

The gauge-corrected ERA5 data set appeared to provide improved estimates of total precipitation in some storms, but mixed representations in others. There was a general trend where lower magnitudes tended to be slightly overestimated and higher magnitudes tended to be underestimated. Table 9 (for the North Island) and Table 10 (for the South Island) summarise conclusions from the verification process.

Table 9: Summary of total precipitation storm verification - North Island

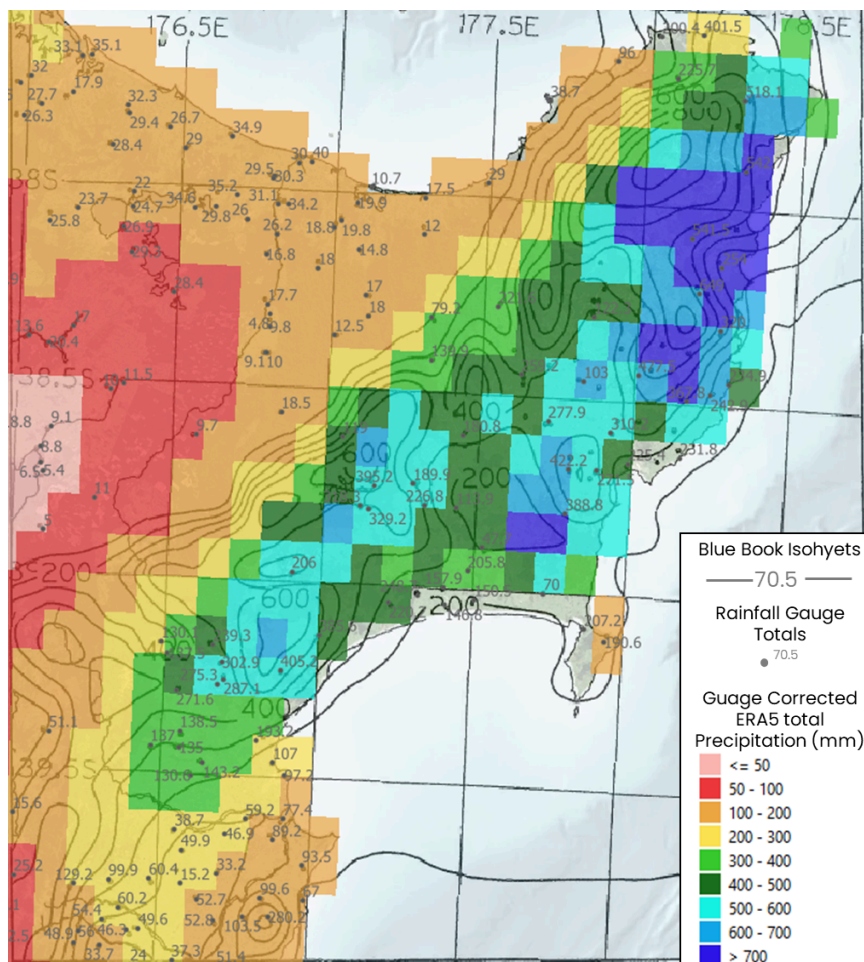
Storm		Verification		
Region	Date	Isohyets	Gauges	Notes
Gisborne	6 - 8 March 1988	Good	Good	Improved spatial pattern. Peak magnitudes are well represented. Overestimated lower precipitation totals.
Coromandel	11 - 13 Apr 1981	Good	Good	Similar spatial pattern and magnitudes.
Taranaki	22 - 24 Feb 1971	Poor	Poor	Pattern and magnitude - poor
Taranaki	10 - 11 August 1967	Poor	Poor	Spatial pattern is similar. Magnitudes are underestimated.
Waikato	1 - 2 Feb 1967	Good	Good	Spatial pattern is similar. Magnitudes are similar.
Eastern BoP	9 - 10 Mar 1964	Poor	Good	Overestimates low gauge totals. Provides a good match with higher gauge totals. Poor match with isohyets is probably more a reflection of a lack of gauge data to generate isohyets.
Waikato	22 - 24 Feb 1958	Good	Mixed	Similar values and improved spatial pattern in most regions. However, it does not capture larger magnitudes in the Tongariro area.
Central SI	19 - 21 Dec 1984	Mixed	Good	Peak gauge magnitudes are well represented. Low gauge magnitudes tend to be overestimated. Very similar spatial pattern to isohyets, however, magnitudes are quite different.

Table 10: Summary of total precipitation storm verification - South Island

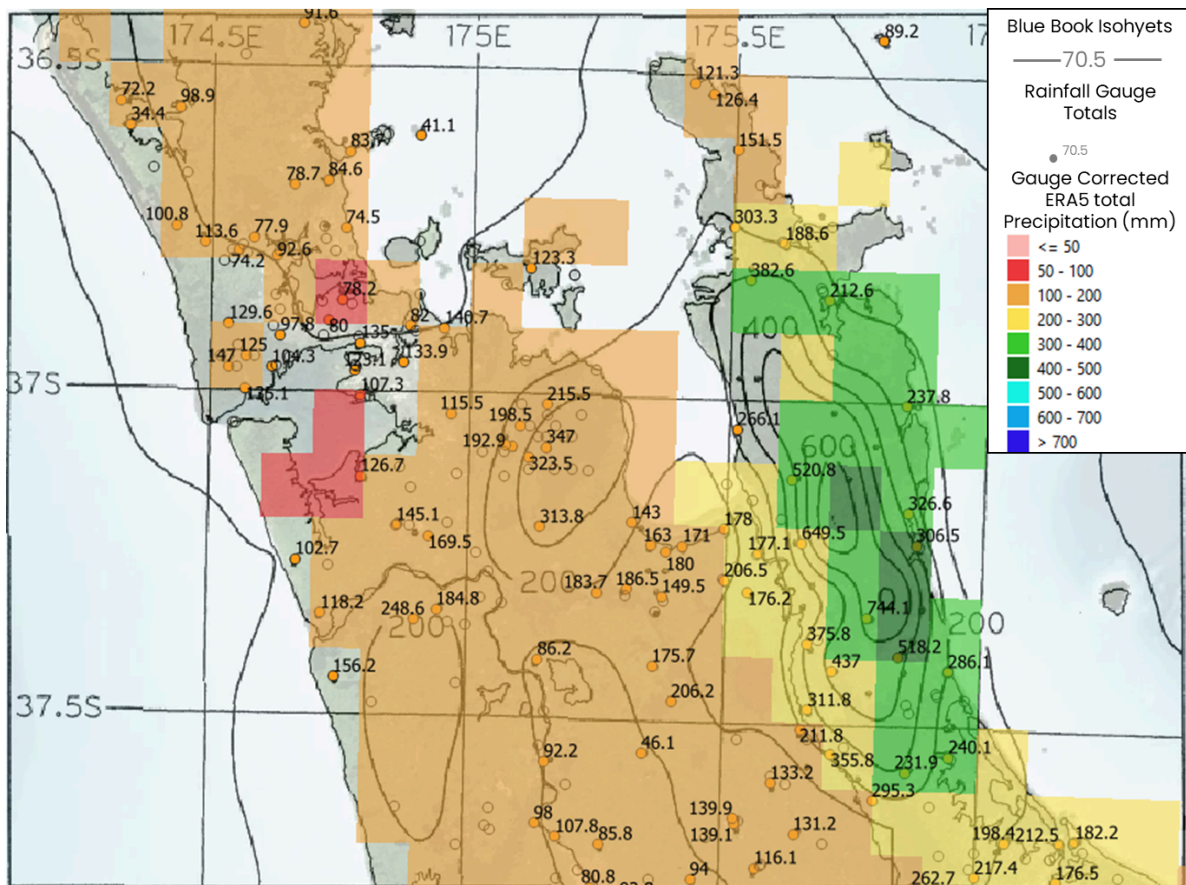
Storm		Verification		
Region	Date	Isohyets	Gauges	Notes
Southland	25 - 27 Jan 1984	Mixed	Mixed	Peak gauge magnitudes are well represented, except for one gauge which recorded an especially high value. Low gauge magnitudes tend to be overestimated. Very similar spatial pattern to isohyets, however, magnitudes are quite different.
Clutha	10 - 12 Jan 1983	Poor	Mixed	Good match with lower gauge totals. Underestimates higher gauge totals. Very different spatial pattern and

				magnitudes in mountainous areas.
Waitaki	22 - 24 Dec 1979	Poor	Good	Good match with gauge totals in most areas. Very different spatial pattern and magnitudes to isohyets.
Canterbury	30 Nov - 2 Dec 1979	Poor	Poor	Poor match with gauge totals. Very similar spatial pattern to isohyets, however, underestimates magnitudes.
Clutha	12 - 14 Oct 1978	Good	Good	Generally tends to give lower magnitudes in higher areas, and slightly higher magnitudes in low lying areas. Similar spatial patterns.
Southern NZ	23 - 25 Apr 1967	Poor	Mixed	Completely different spatial pattern to isohyets. Good match with gauge totals in low lying areas. Good match with gauge totals in some alpine areas, but a poor match in others.
Waitaki	8 - 10 Mar 1967	Mixed	mixed	Very different spatial pattern to isohyets in some alpine areas. Good match with gauge totals in low lying areas and some alpine areas. Poor match in other alpine areas.
Clutha	17 - 19 Nov 1957	Poor	Poor	Somewhat similar spatial pattern. Does not capture peak magnitudes in higher alpine areas.
Clutha	30 Jan - 1 Feb 1952	Poor	Mixed	Seems to underpredict magnitudes in higher alpine areas.

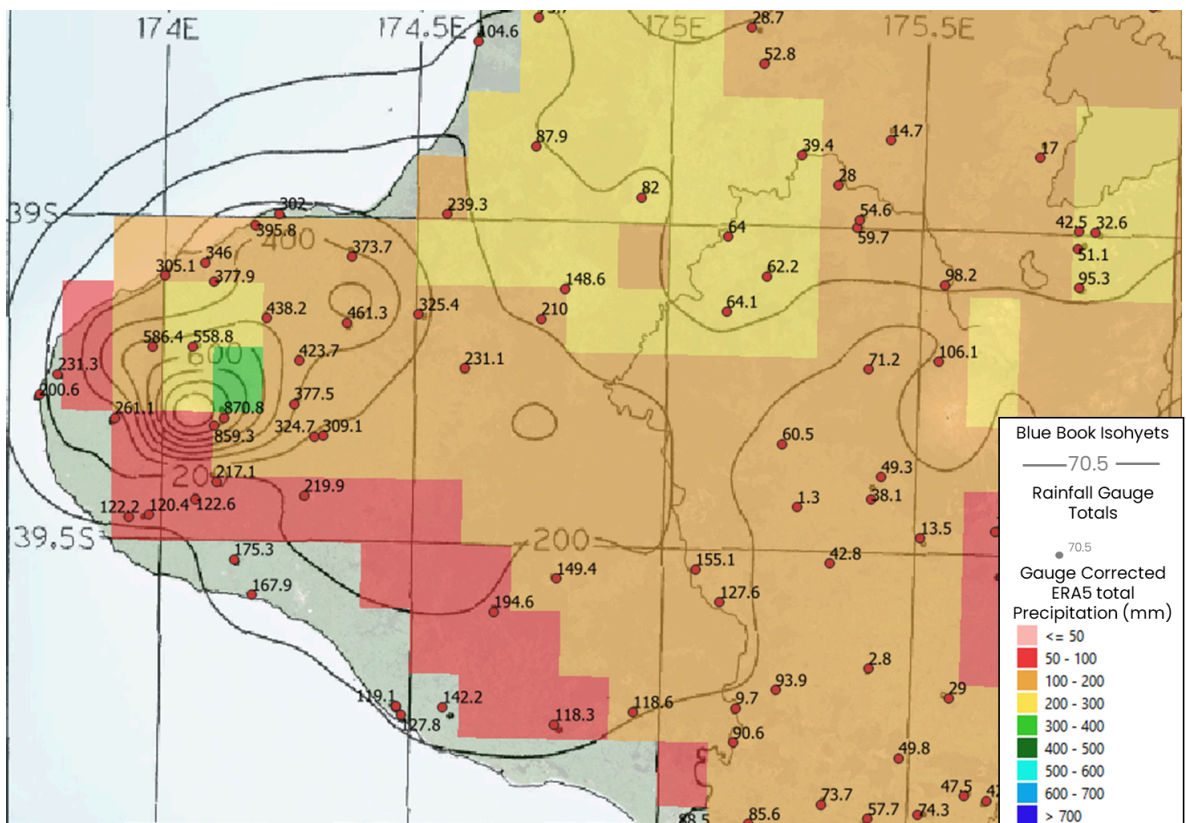
North Island storms



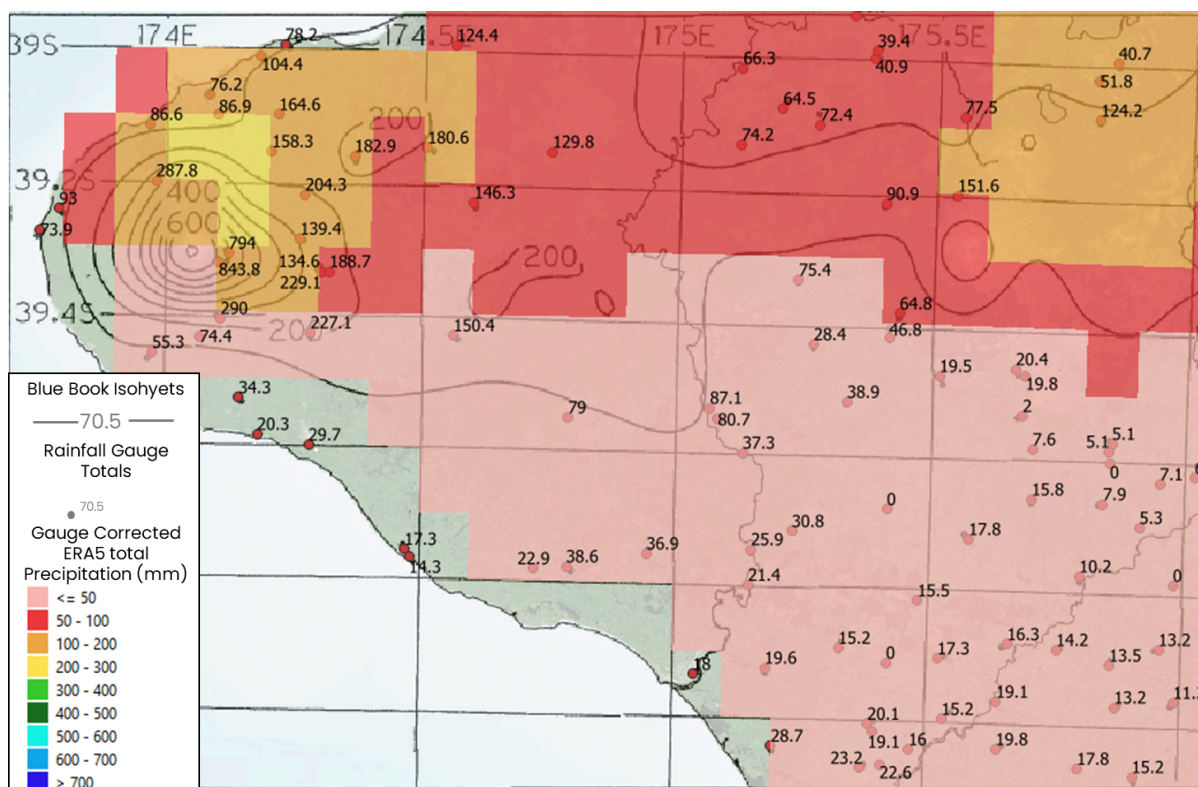
Gisborne: 6 - 8 March 1988



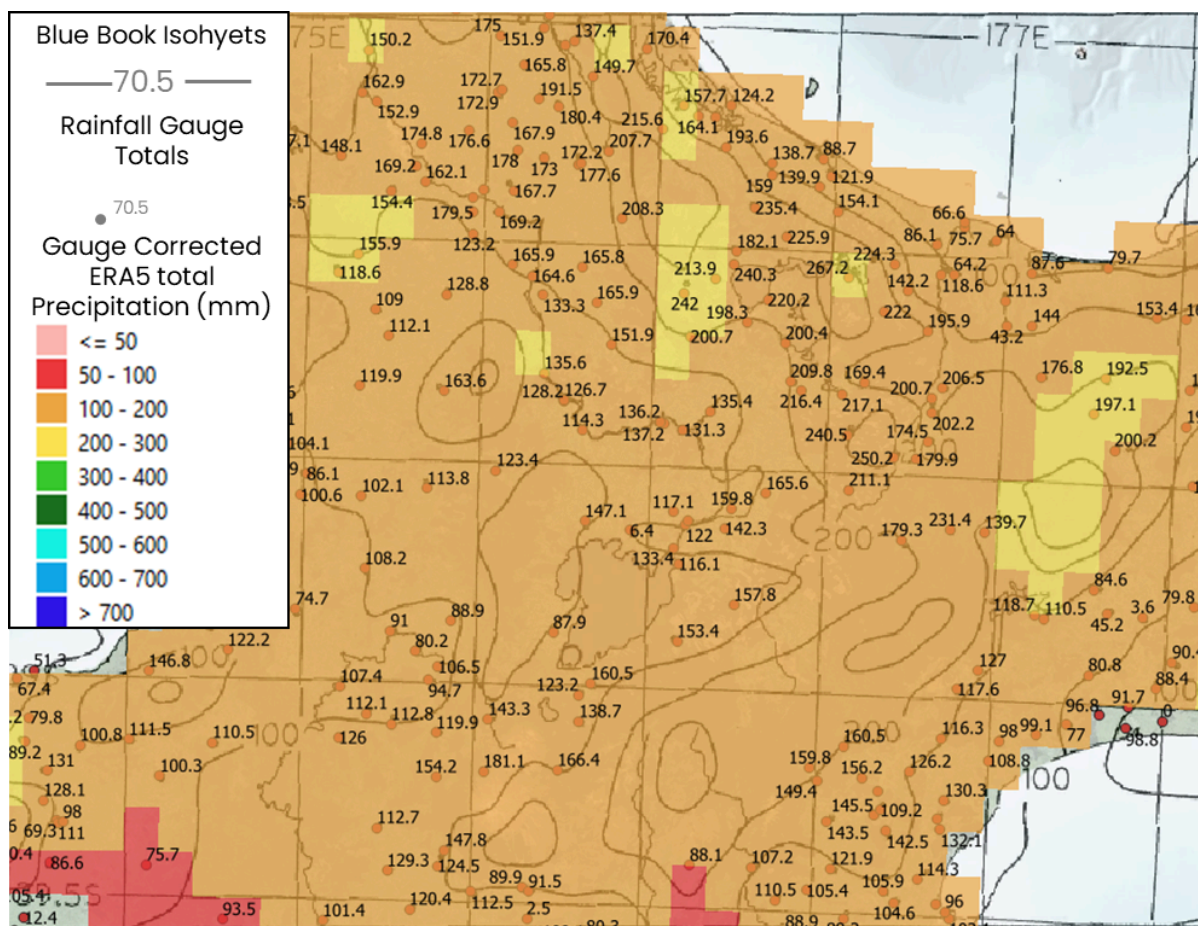
Coromandel: 11 - 13 April 1981



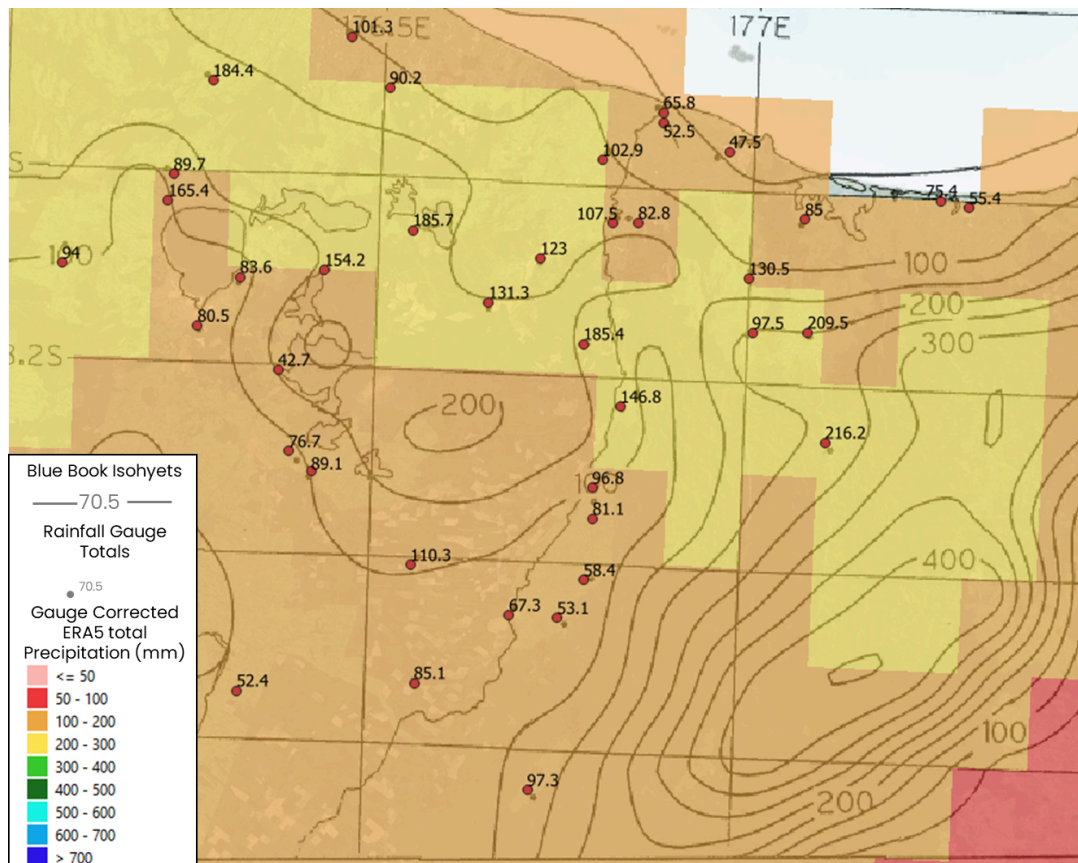
Taranaki: 22 - 24 February 1971



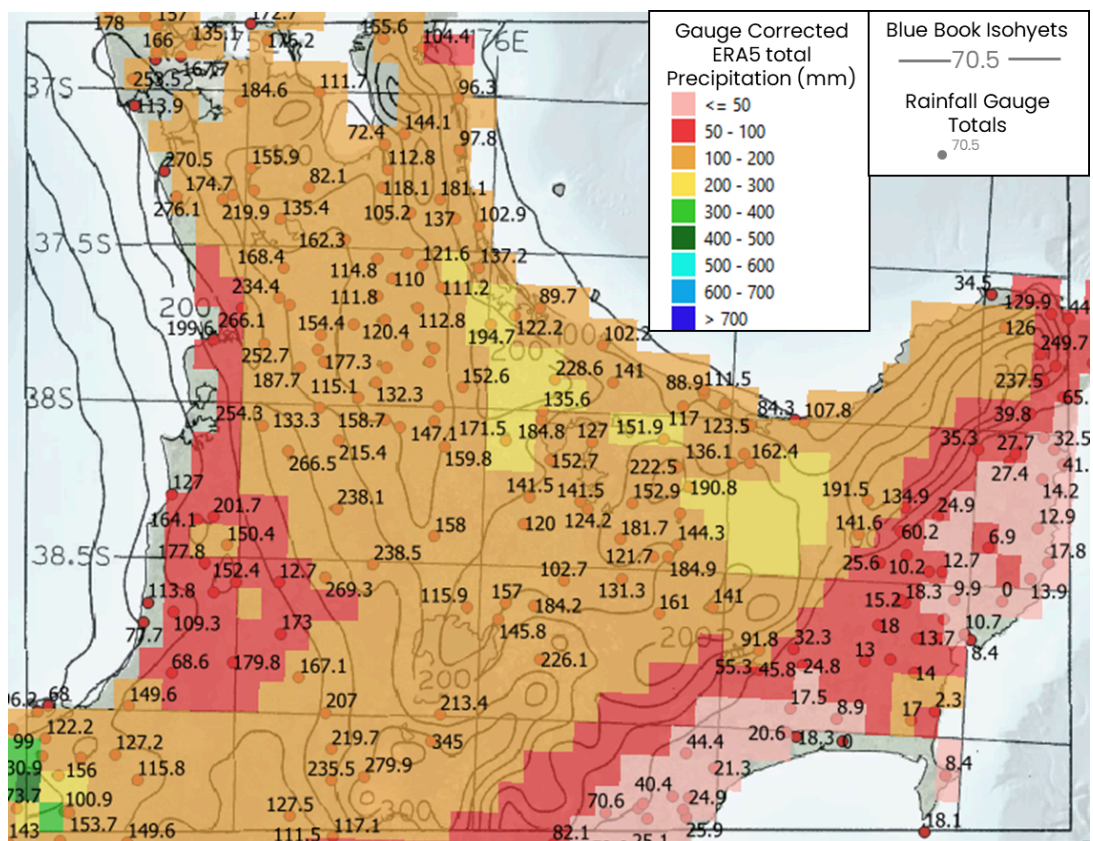
Taranaki: 10 - 11 August 1967



Waikato: 1 - 2 February 1967

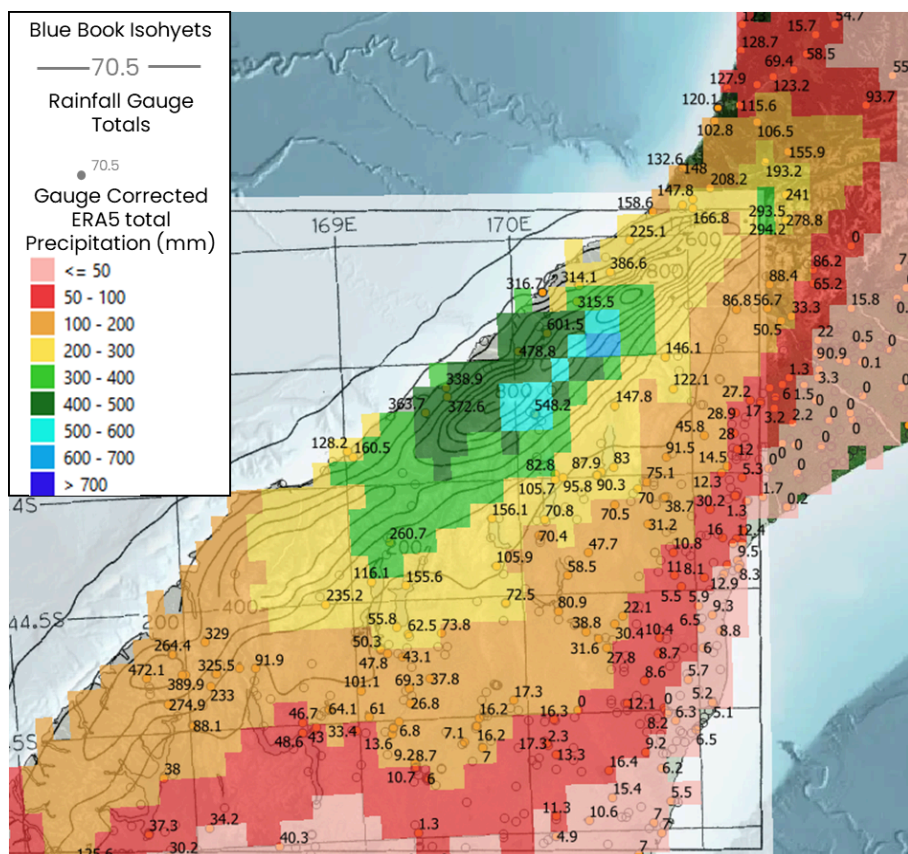


Eastern Bay of Plenty: 9 - 10 March 1964

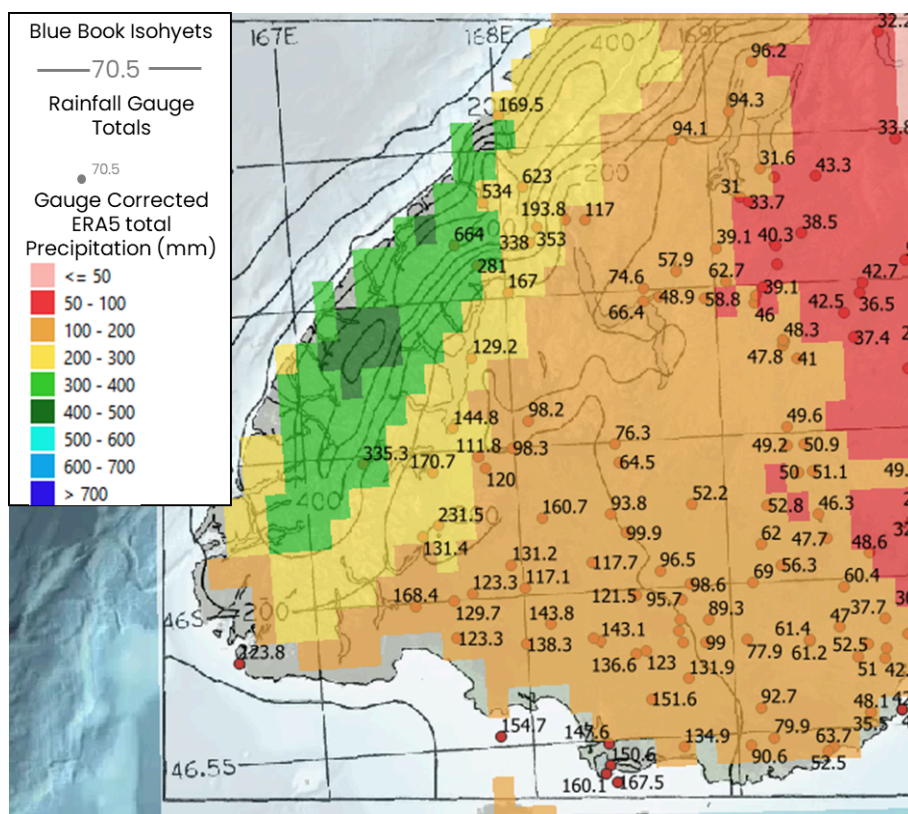


Waikato: 22 - 24 February 1958

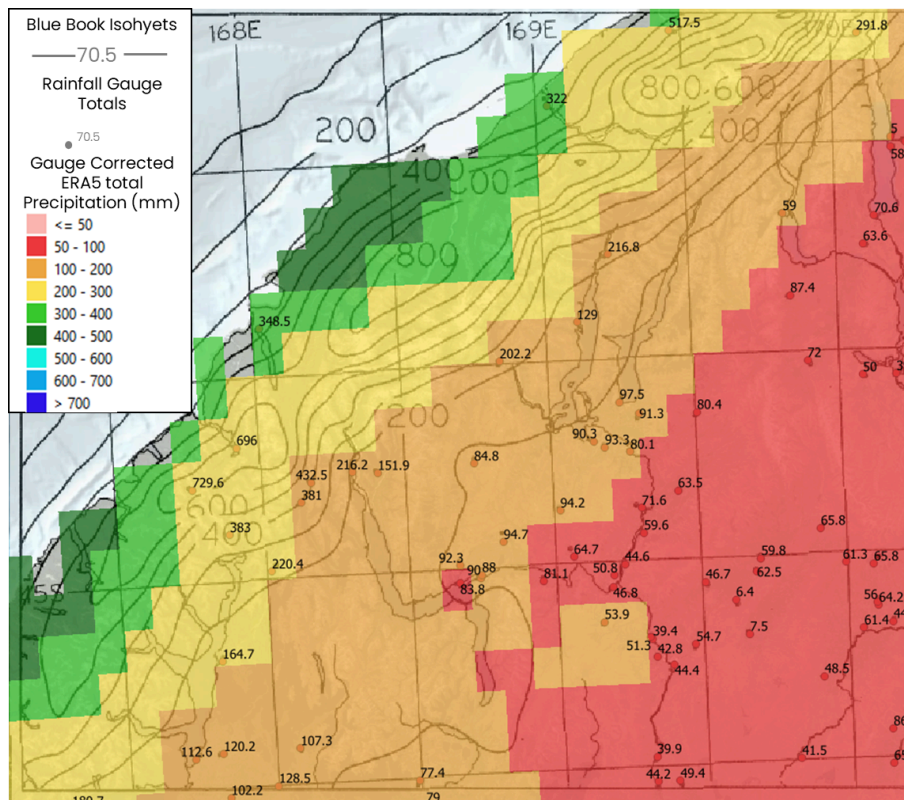
South Island storms



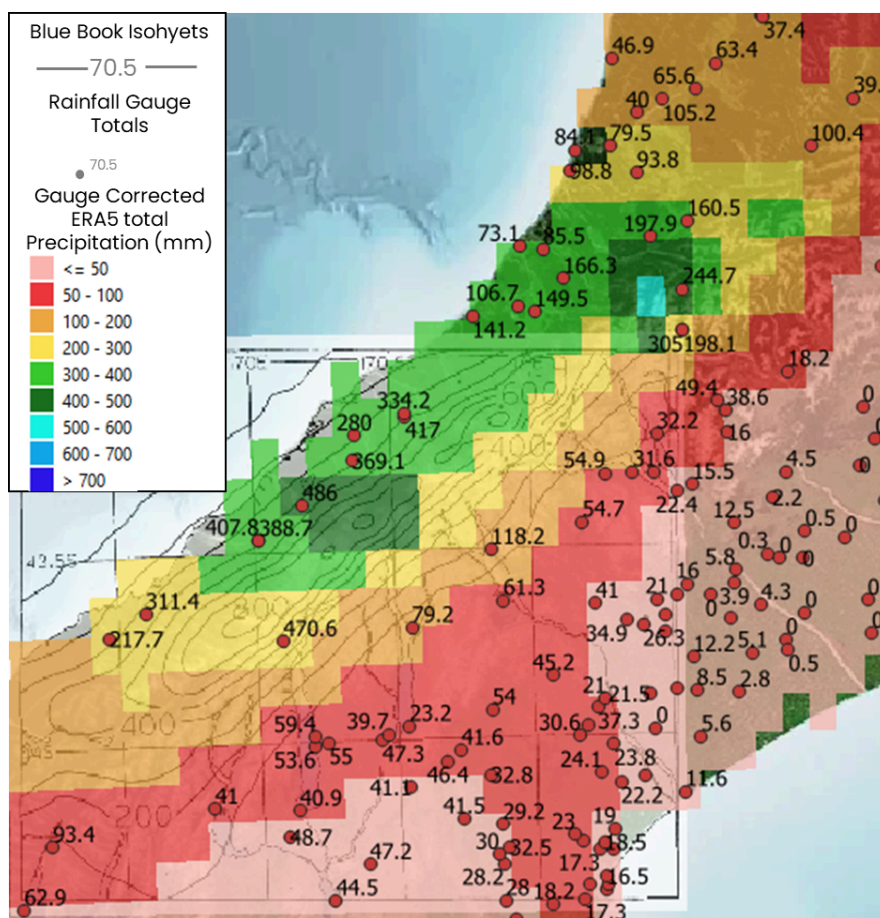
Central South Island: 19 - 21 December 1984



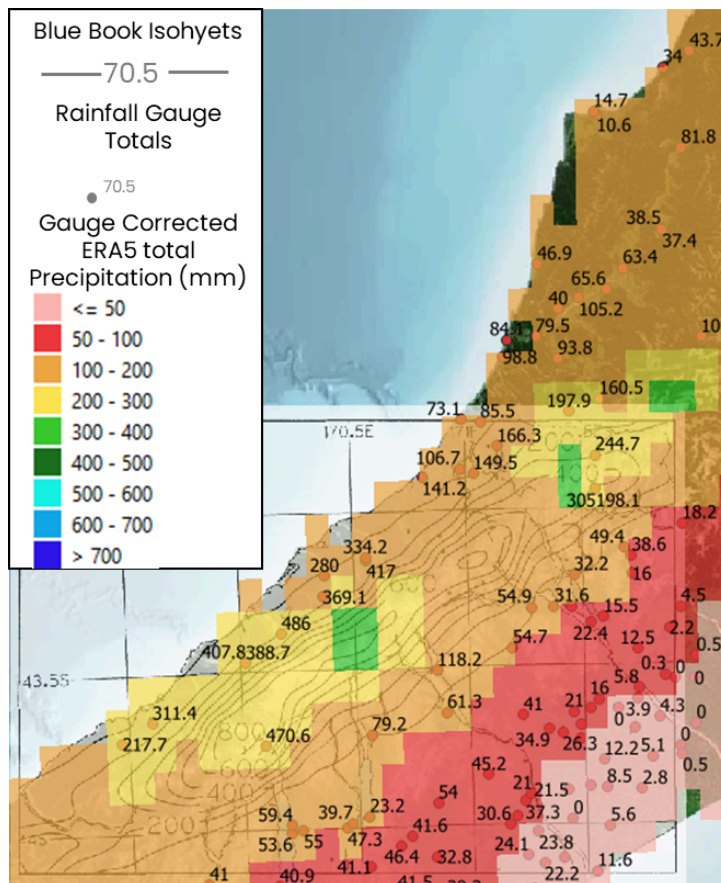
Southland: 25 - 27 January 1984



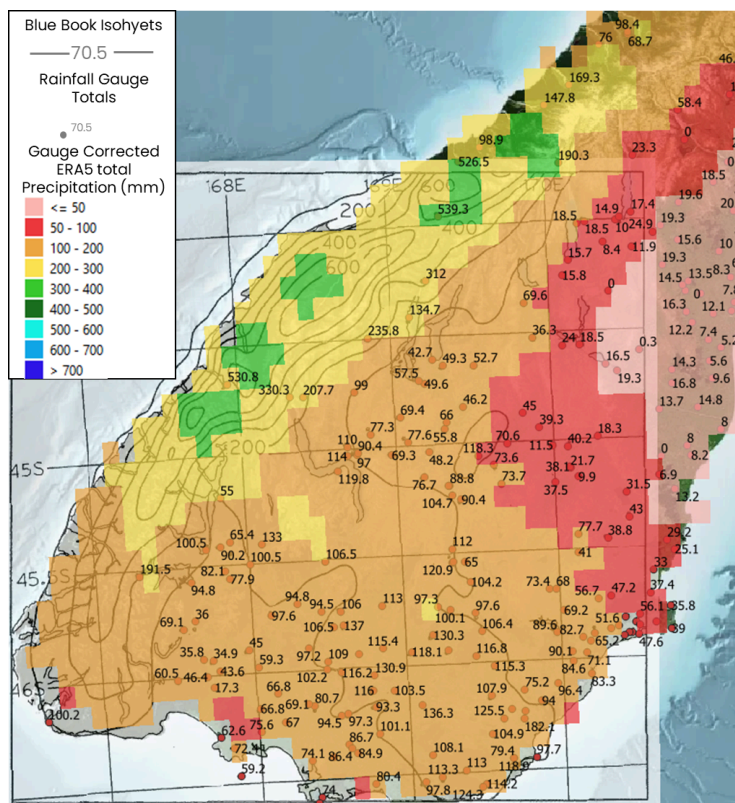
Clutha Catchment: 10 - 12 January 1984



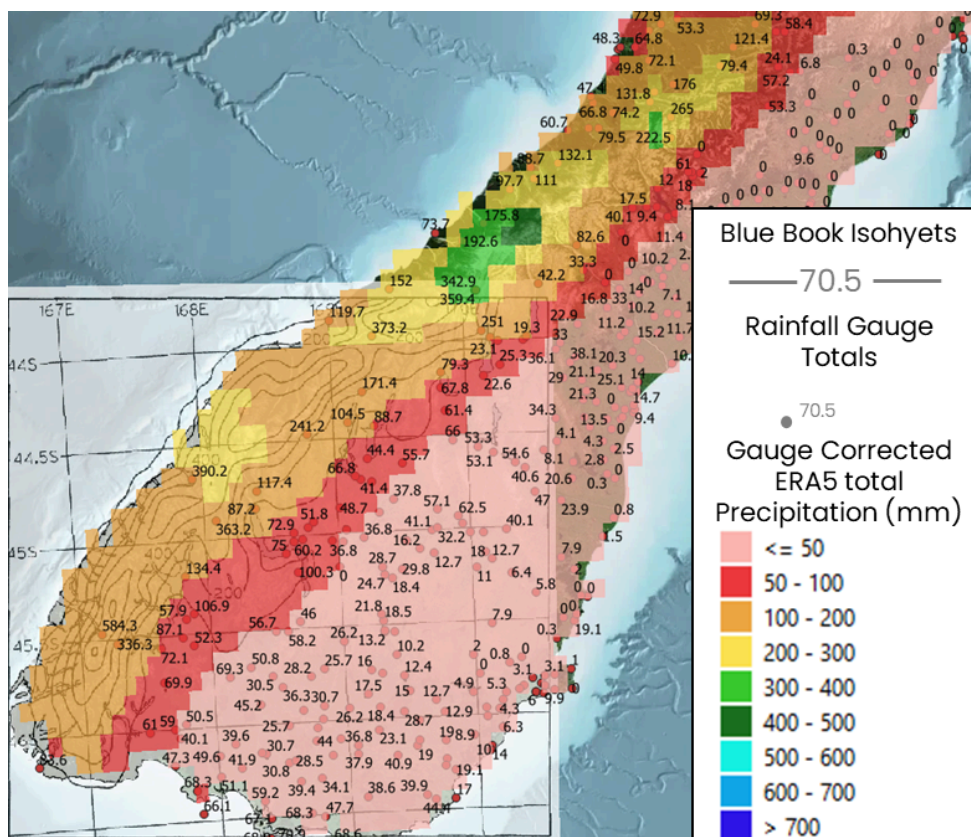
Waitaki Catchment: 22 - 24 December 1979



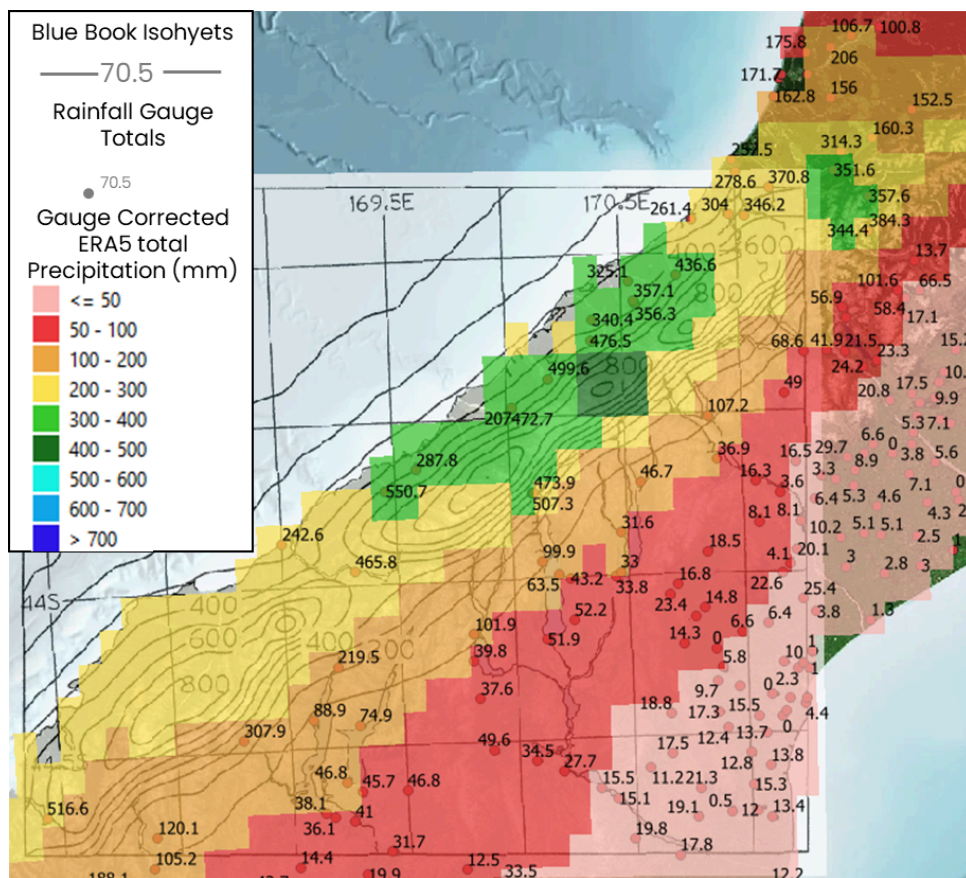
Canterbury: 30 November - 2 December 1979



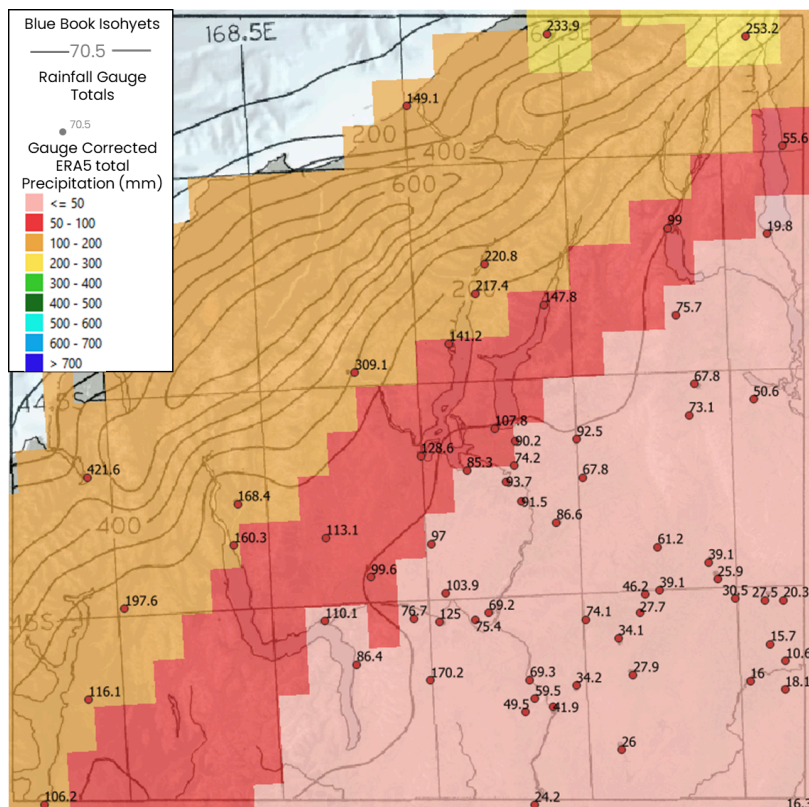
Clutha Catchment: 12 - 14 October 1978



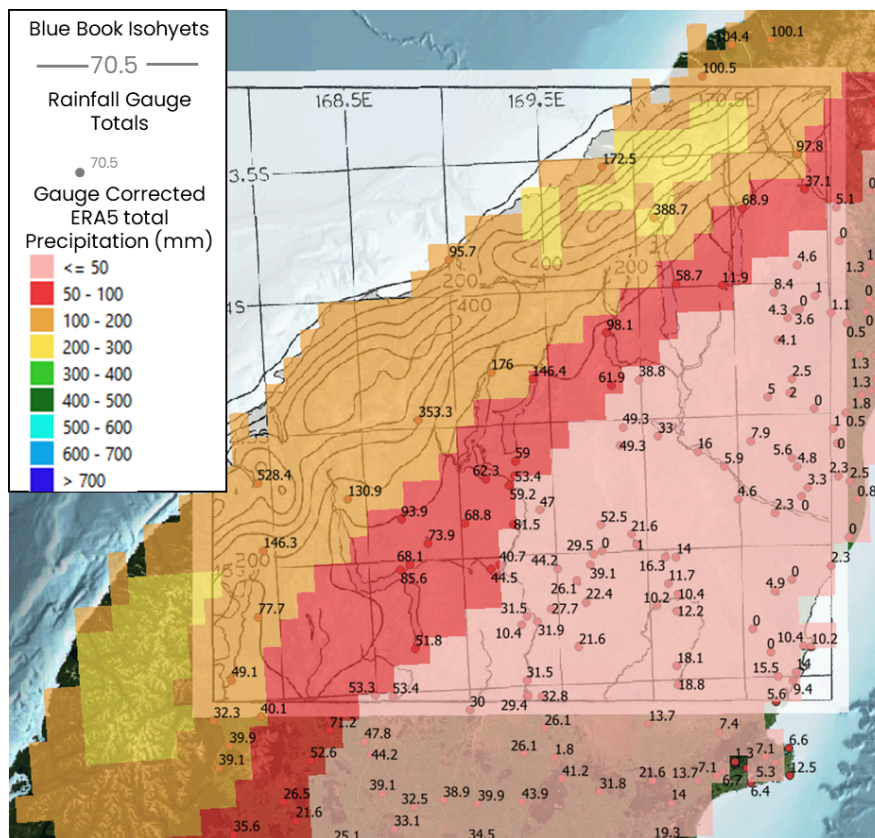
Southern New Zealand: 23 - 25 April 1967



Waitaki Catchment: 8 - 10 March 1967



Clutha Catchment: 17 - 19 November 1957



Clutha Catchment: 30 January - 1 February 1952

Appendix B: Storm dew point temperature verification

General

Table B-1: Summary of dew point temperature storm verification - North Island

Storm		Dew point temperature estimate			Moisture maximisation ratio		
Region	Date	Blue Book	ERA5	Difference	Blue Book	ERA5	Difference
Gisborne	6 - 8 March 1988	18 to 18.5*	18.9	0.4 to 0.9	1.68	1.45	-0.13
Bay of Plenty	19 March 1979	21	21	0	1.24	1.22	-0.02
Taranaki	22 - 24 Feb 1971	20	20.4	0.4	1.3	1.33	0.03
Taranaki	13 May 1972	15	15.8	0.8	1.2	1.53	0.33

* Note: Blue Book value of 18.5 in Appendix 1, but a value of 18.0 in Appendix 2.

Table B-2: Summary of dew point temperature storm verification - South Island

Storm		Dew point temperature estimate			Moisture maximisation ratio		
Region	Date	Blue Book	ERA5	Difference	Blue Book	ERA5	Difference
Central SI	22 Nov 1984	16	18.6	2.6	1.19	1.46	0.27
Clutha	10 - 12 Jan 1983	17	15.7	-1.3	1.43	1.66	0.23
Waitaki	22 - 24 Dec 1979	17	19.3	2.3	1.49	1.40	-0.09
Marlborough	12 March 1975	18	20	2	1.49	1.31	-0.18
N Westland	30 August 1970	12	14.6	2.6	1.31	1.32	0.01
Buller	8 September 1969	12	14.3	2.3	1.31	1.25	-0.06
Banks Peninsula	10 April 1968	16	16.8	0.8	1.09	1.56	0.47
S Westland	14 March 1965	16	17.9	1.9	1.7	1.62	-0.08

North Island Storms

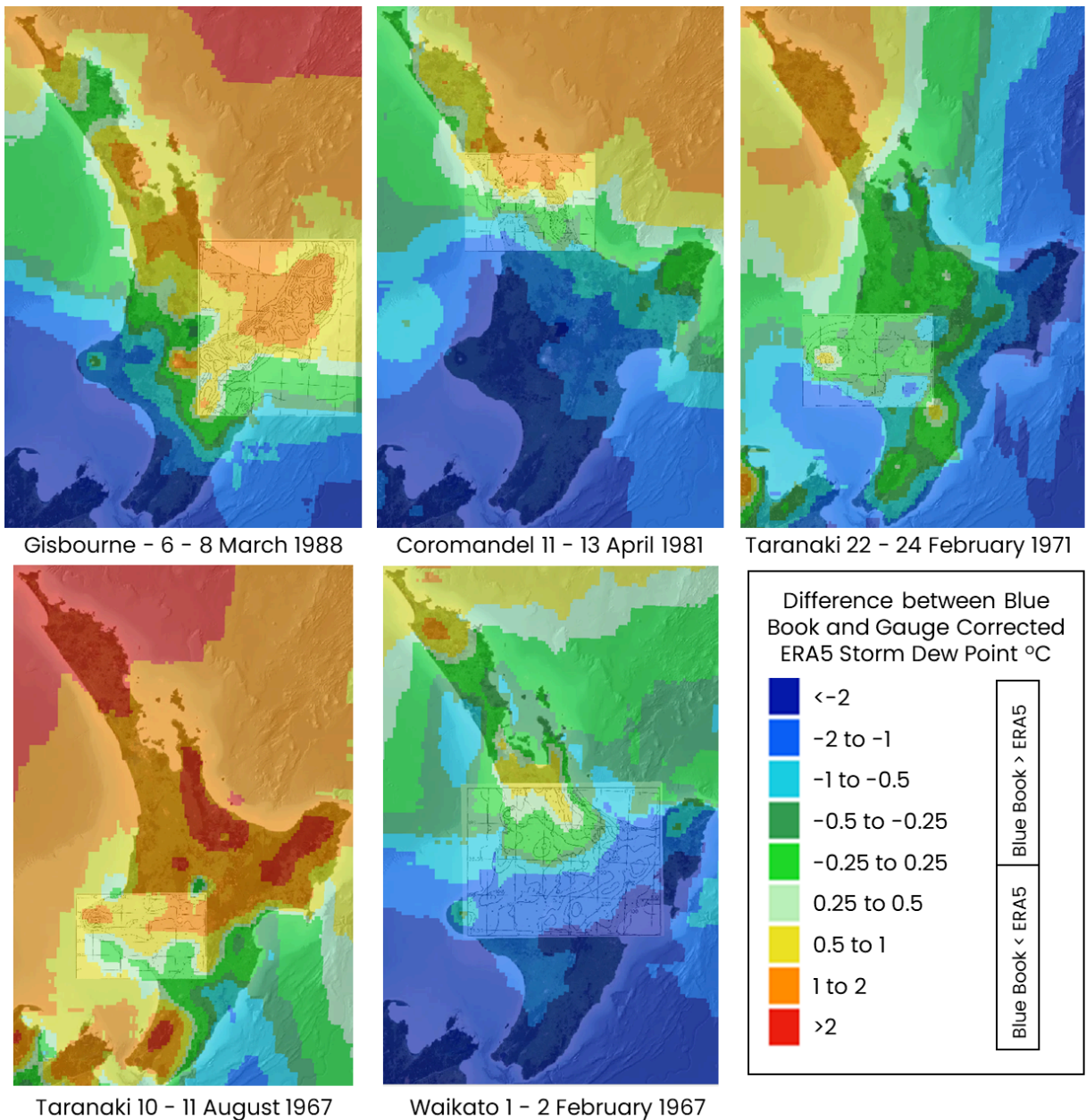


Figure B-1: The difference between the *single* Blue Book storm dew point temperature estimate and MVP (ERA5) storm dew point estimate *map* (Blue Book minus MVP). The fields in the background show the total precipitation field from the Blue Book over the area of the storm. *Note: Waikato 1967 event was not included in the MVP storm catalogue (and is therefore not present in table B-1).*

South Island storms

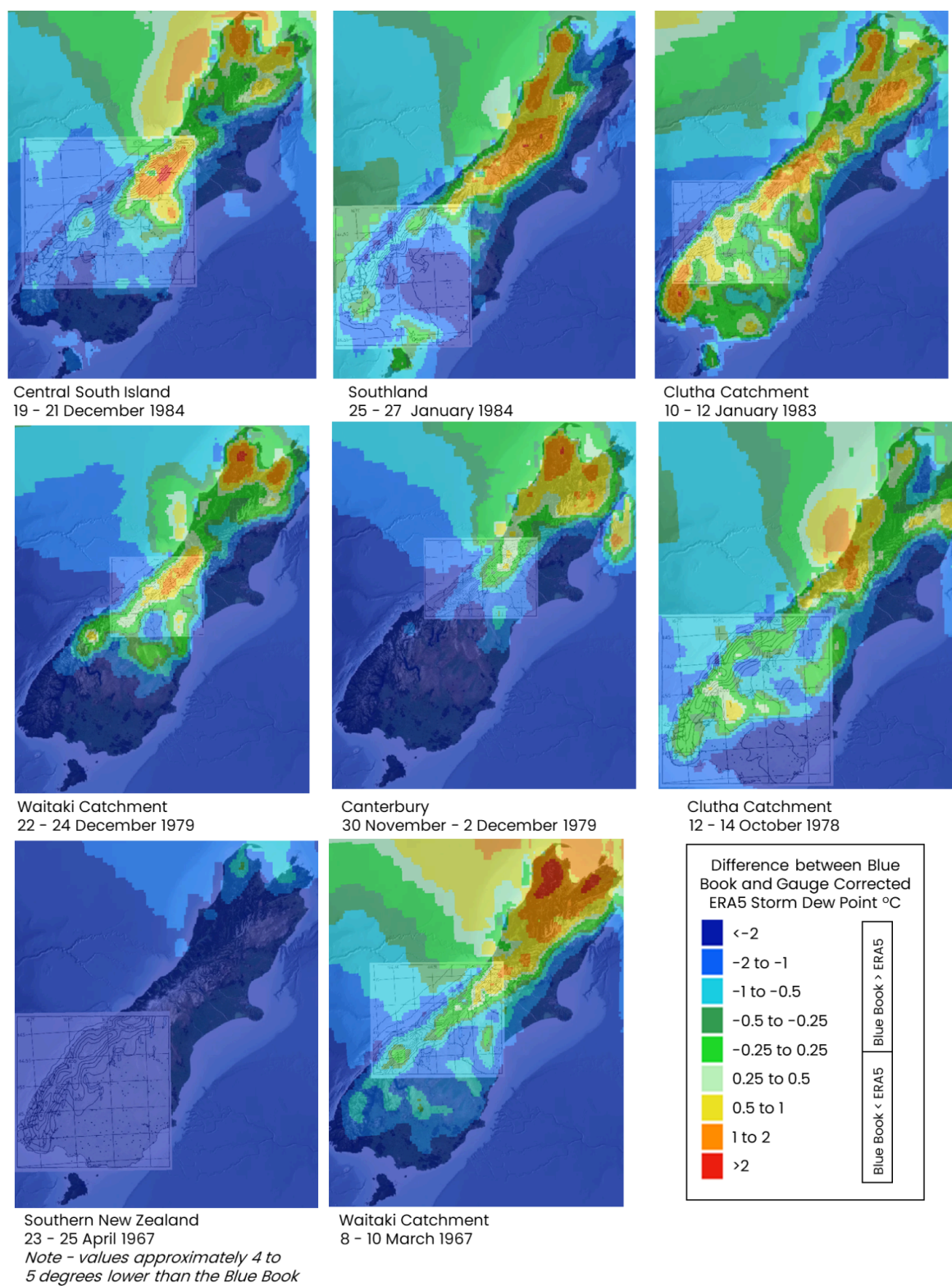


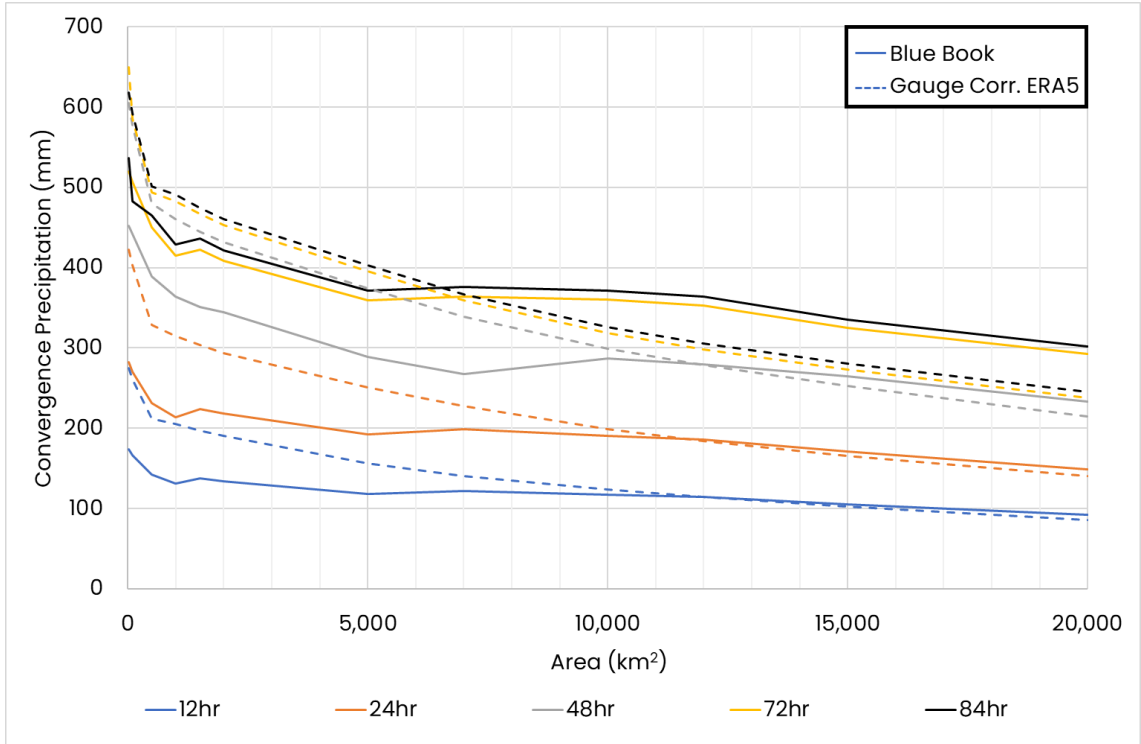
Figure B-2: The difference between the *single* Blue Book storm dew point temperature estimate and MVP (ERA5) storm dew point estimate *map* (Blue Book minus MVP). The fields in the background show the total precipitation field from the Blue Book over the area of the storm.

Appendix C - Convergence depth-area duration - storm verification

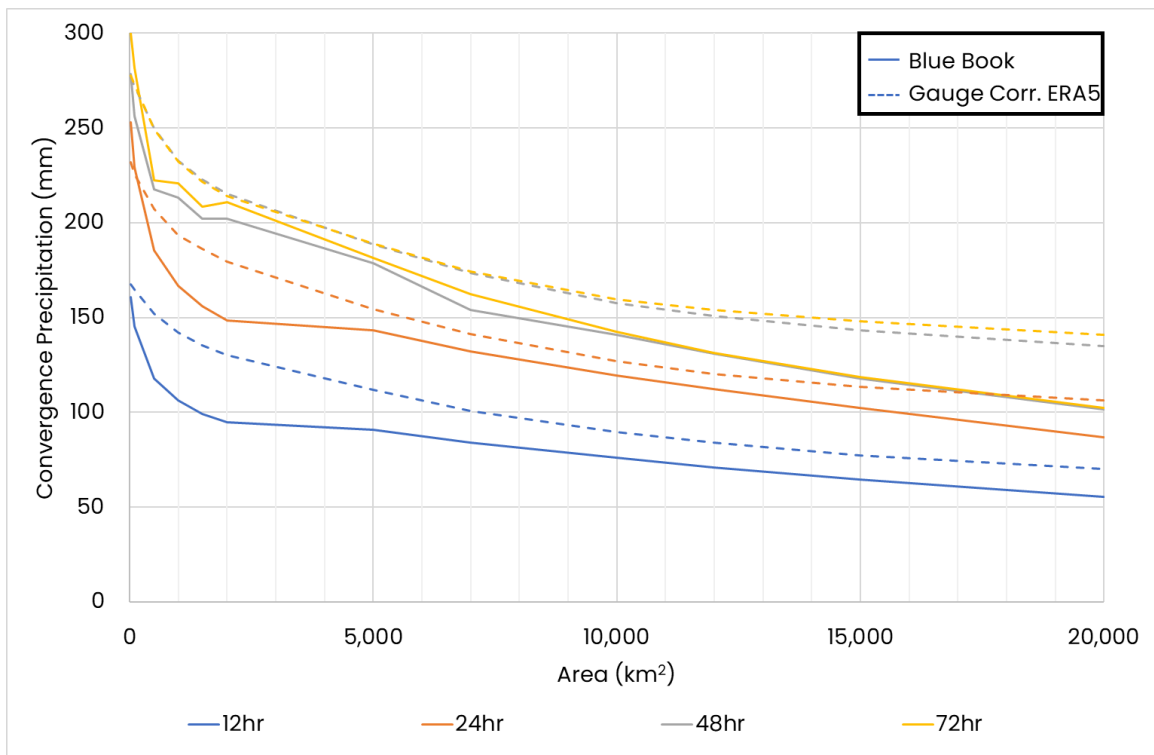
General

The following figures present convergence precipitation estimates from the Blue Book and the MVP (for those events which were selected for detailed analysis in both the Blue Book and the MVP). The figures demonstrate that despite large differences in methodology, both the Blue Book and MVP methods tend to generate similar magnitudes of convergence precipitation over the various durations and areas of interest for most events. Generally, the MVP estimates tend to be higher than the Blue Book estimates. This was expected given that the MVP estimates were derived directly from the area with the highest convergence precipitation during the event, whereas the Blue Book estimates were derived taking the convergence component from the area of highest total precipitation during the event.

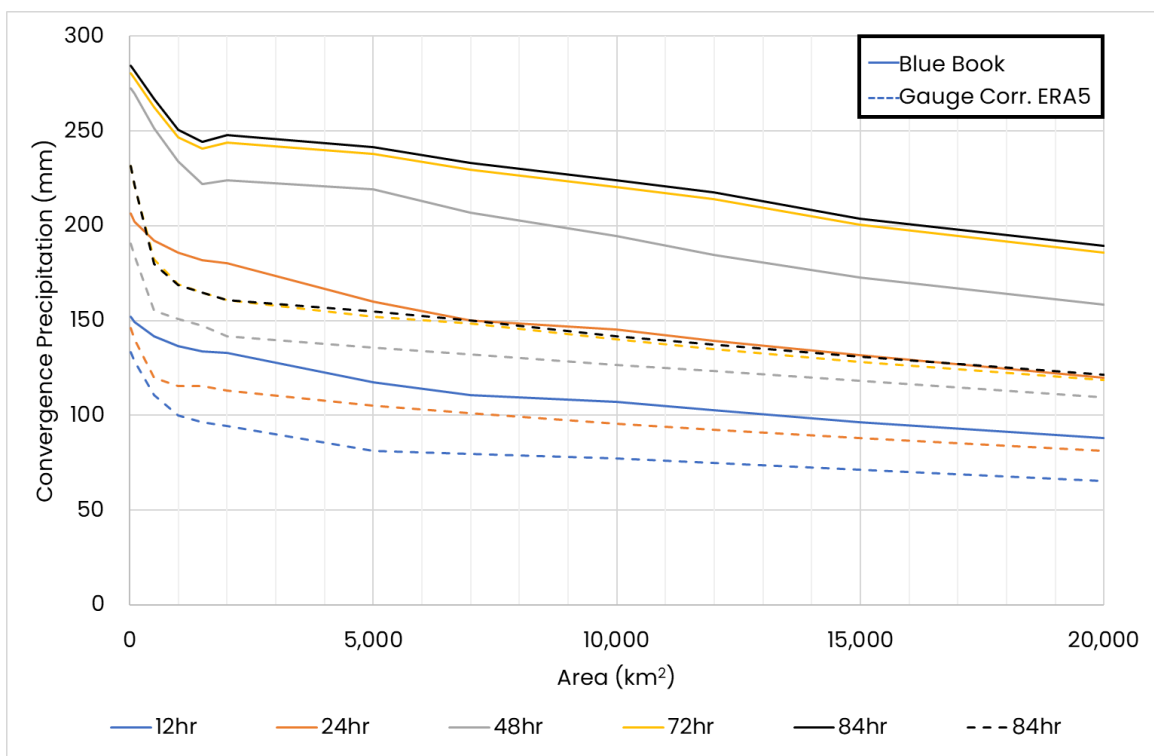
North Island Storms



Gisbourne: 6 - 8 March 1988

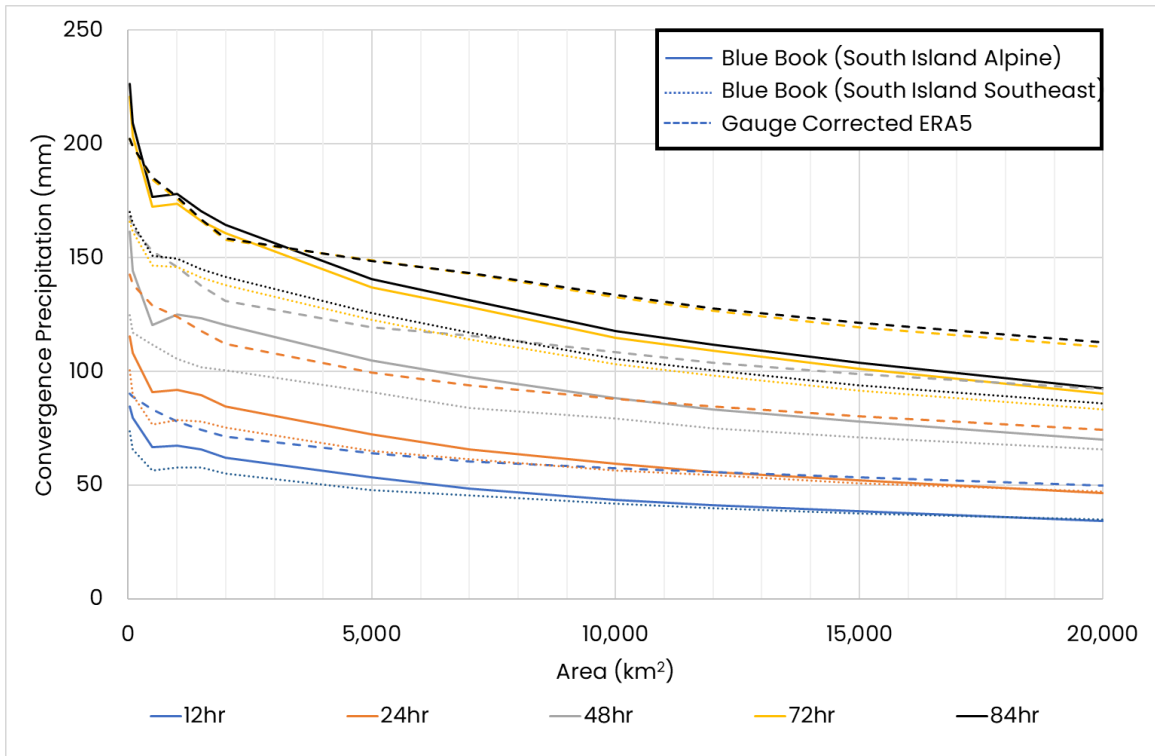


Taranaki: 22 - 24 February 1971

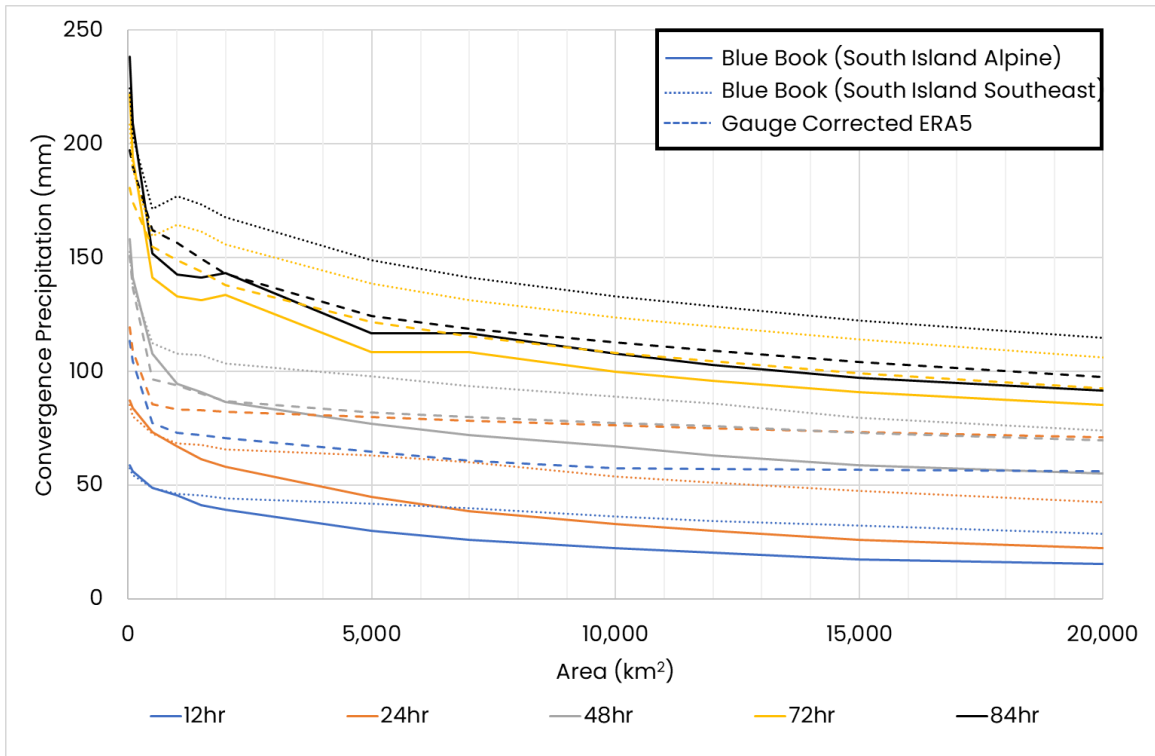


Waikato: 22 - 24 February 1958

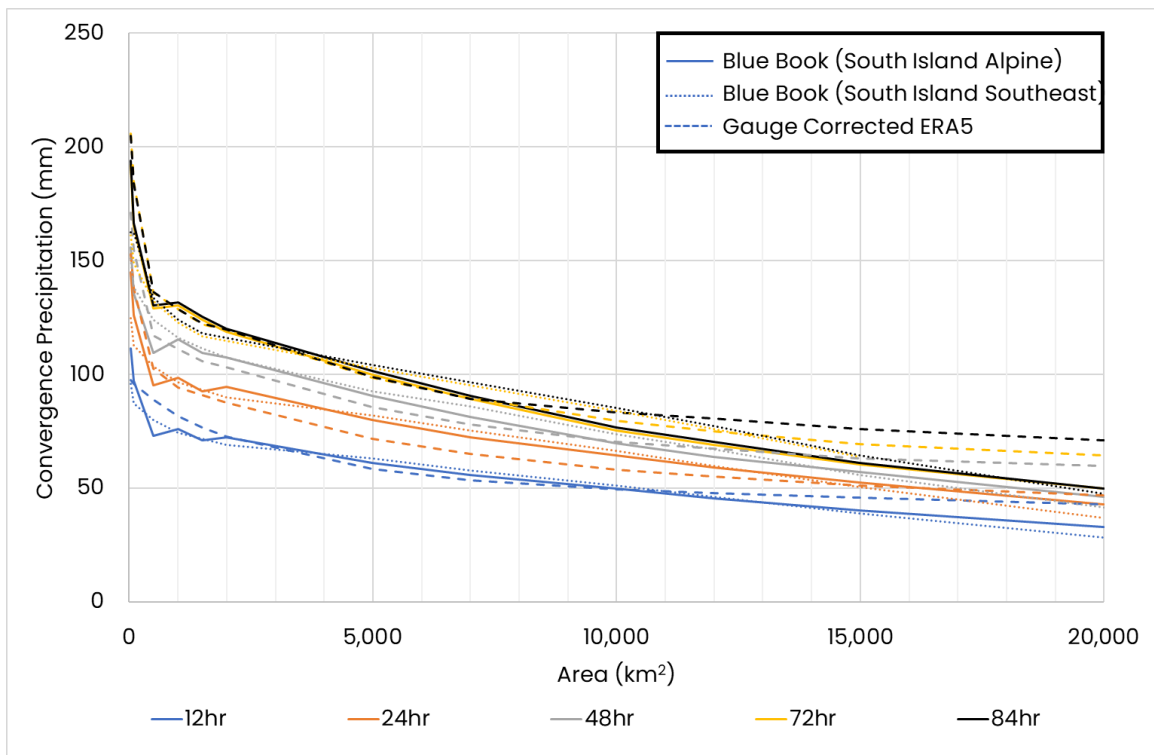
South Island storms



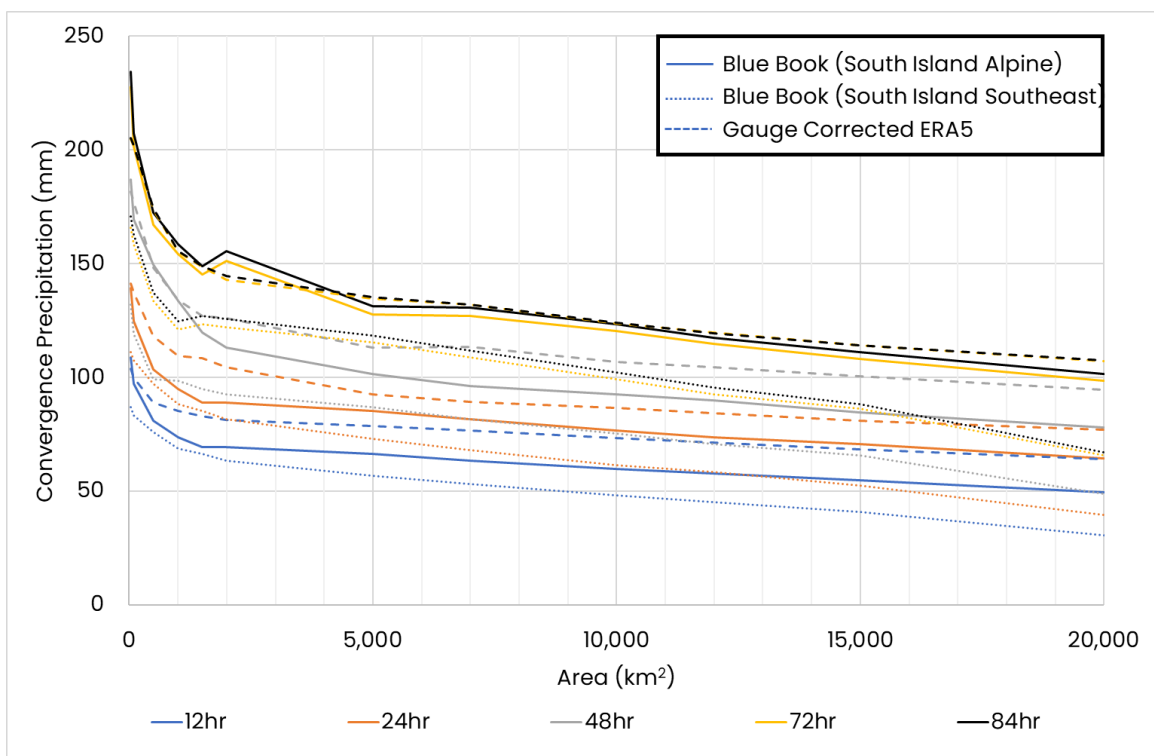
Central South Island: 19 - 21 December 1984



Clutha Catchment: 10 - 12 January 1983



Waitaki Catchment: 22 - 24 December 1979



Clutha Catchment: 17 - 19 November 1957

Appendix D - MVP storm catalogue of events between 1960 and 2019

Start date/time	End date/time	Max. total precip (mm)	Min. latitude	Max. latitude	Min. longitude	Max. longitude
1988-03-04 00:00	1988-03-18 03:00	643.2	-41.2	-37.7	172.5	178.4
1958-12-06 07:00	1958-12-25 16:00	176.3	-40.7	-35.1	173.6	176.6
1956-04-11 09:00	1956-04-30 12:00	274.1	-42.4	-36.5	171.5	175.9
1972-03-02 09:00	1972-03-17 04:00	305.0	-38.5	-36.5	174.8	177.7
1984-11-28 04:00	1984-12-23 15:00	312.2	-45.2	-38.5	167.7	174.8
1995-03-24 02:00	1995-04-12 18:00	231.1	-40.5	-36.5	175.4	178.4
1962-02-25 22:00	1962-03-15 01:00	284.3	-45.4	-37.3	170.0	178.4
1974-04-12 23:00	1974-04-29 02:00	265.3	-41.6	-38.9	172.5	177.9
1967-11-04 17:00	1967-11-25 13:00	278.7	-45.6	-36.5	167.3	175.2
1990-03-05 19:00	1990-03-20 23:00	294.6	-44.6	-37.8	169.1	177.9
1968-04-06 08:00	1968-04-16 05:00	470.6	-46.1	-35.2	168.7	175.7
1988-12-26 18:00	1989-01-10 09:00	133.6	-45.7	-35.1	169.4	175.2
1955-05-30 02:00	1955-06-17 19:00	219.0	-46.4	-35.4	166.9	176.8
1955-02-12 02:00	1955-02-21 14:00	653.5	-44.3	-42.1	170.8	172.1
1950-04-09 01:00	1950-04-16 04:00	324.0	-36.9	-34.9	173.2	175.5
1989-05-19 07:00	1989-05-31 04:00	596.2	-40.5	-38.2	176.6	178.3
1979-05-03 01:00	1979-05-19 03:00	425.8	-43.4	-39.3	170.3	174.1
1979-12-21 10:00	1980-01-05 06:00	321.3	-44.1	-39.1	169.9	176.8
2014-04-02 18:00	2014-04-20 21:00	321.9	-44.6	-36.8	170.9	178.0
1957-11-16 22:00	1957-12-02 14:00	430.3	-45.6	-42.0	167.3	172.2
2005-12-02 11:00	2005-12-23 20:00	118.5	-46.2	-38.0	167.9	176.0
1998-10-06 15:00	1998-10-13 20:00	360.9	-43.1	-38.4	170.3	175.6
1965-01-10 18:00	1965-01-25 07:00	171.3	-37.3	-34.9	173.3	175.9
2001-11-29 19:00	2001-12-24 17:00	307.9	-43.1	-37.6	170.3	178.1
1969-09-01 20:00	1969-09-14 00:00	669.6	-45.2	-40.7	167.8	172.5
1985-12-30 14:00	1986-01-14 23:00	182.2	-46.1	-37.8	167.3	177.0
2004-02-08 19:00	2004-02-21 20:00	224.6	-41.3	-39.2	173.9	176.6
1950-05-23 04:00	1950-05-29 04:00	440.5	-40.9	-38.0	173.8	175.6
2019-11-04 07:00	2019-11-20 15:00	186.5	-45.9	-40.6	167.1	175.4
2011-04-21 21:00	2011-05-08 08:00	329.1	-40.6	-37.6	175.8	178.4
1965-03-13 01:00	1965-03-22 01:00	350.5	-45.0	-40.5	168.0	176.6
2006-04-20 12:00	2006-04-30 21:00	204.4	-46.1	-38.6	169.9	178.2
1978-06-14 18:00	1978-06-25 13:00	156.9	-39.9	-35.3	173.8	177.9
1960-11-23 14:00	1960-12-14 14:00	137.6	-40.6	-35.9	174.0	178.3
1960-09-01 06:00	1960-09-17 13:00	223.6	-43.1	-35.0	170.3	176.5
1971-02-19 23:00	1971-02-26 02:00	236.3	-40.6	-34.5	172.8	176.1
1955-05-03 01:00	1955-05-10 04:00	442.4	-42.7	-39.2	171.1	175.0

2010-05-22 12:00	2010-05-30 03:00	270.4	-45.8	-43.6	169.9	172.1
2007-06-28 10:00	2007-07-12 06:00	199.2	-39.2	-35.1	173.6	175.9
2006-06-09 18:00	2006-06-25 02:00	408.4	-44.1	-38.2	170.4	178.3
1991-01-20 02:00	1991-02-02 15:00	317.0	-43.3	-38.0	170.0	176.1
2002-01-08 00:00	2002-01-20 13:00	268.3	-45.2	-42.7	170.5	173.4
1977-06-25 07:00	1977-07-05 02:00	201.4	-44.1	-38.0	171.7	175.6
1989-12-21 08:00	1990-01-05 10:00	486.1	-45.6	-39.2	167.3	174.2
1966-02-14 23:00	1966-02-24 15:00	234.3	-44.7	-35.8	169.1	176.3
1979-03-02 17:00	1979-03-24 13:00	315.9	-44.1	-35.3	168.3	178.5
2004-08-03 18:00	2004-08-19 08:00	220.6	-46.2	-39.8	166.9	176.9
1999-10-25 11:00	1999-11-12 16:00	256.4	-43.1	-35.3	170.3	177.0
1968-03-02 04:00	1968-03-14 22:00	273.2	-46.4	-44.1	167.6	171.2
1961-01-13 00:00	1961-01-23 17:00	208.7	-39.8	-36.7	174.6	176.9
1956-12-14 13:00	1957-01-06 18:00	152.7	-46.2	-38.0	166.8	175.6
2018-11-15 02:00	2018-12-06 16:00	136.3	-46.1	-40.9	169.1	176.0
2009-05-02 22:00	2009-05-27 01:00	403.5	-45.3	-43.3	167.8	171.5
2008-07-15 11:00	2008-08-05 22:00	280.2	-39.4	-35.1	173.7	176.3
1980-01-13 09:00	1980-01-25 02:00	264.5	-46.0	-38.0	168.7	175.9
1985-06-12 08:00	1985-06-25 20:00	538.6	-41.3	-38.0	173.8	176.6
2016-01-16 14:00	2016-01-29 14:00	293.8	-46.4	-38.4	166.5	178.3
2002-06-24 23:00	2002-07-16 06:00	132.4	-41.3	-36.5	173.9	175.8
1983-01-02 23:00	1983-01-16 15:00	285.6	-46.2	-42.1	166.9	171.9
1974-03-30 18:00	1974-04-10 12:00	396.4	-43.1	-40.5	170.3	173.7
2013-06-30 15:00	2013-07-15 18:00	165.9	-45.7	-38.8	167.3	177.9
2018-02-24 01:00	2018-03-09 13:00	284.6	-41.4	-38.9	173.8	177.7
1952-05-17 11:00	1952-06-13 02:00	142.5	-39.4	-35.6	173.5	176.1
1977-08-21 07:00	1977-09-11 01:00	148.1	-41.3	-37.8	175.1	178.4
1995-03-09 01:00	1995-03-23 20:00	173.6	-46.1	-44.4	166.8	169.2
1975-03-09 00:00	1975-03-17 01:00	357.8	-41.6	-36.7	172.5	176.7
2000-09-28 06:00	2000-10-09 12:00	172.5	-45.6	-39.2	167.6	175.6
1983-10-18 19:00	1983-10-31 12:00	320.3	-42.4	-35.2	171.5	176.7
1958-05-01 13:00	1958-05-13 07:00	244.9	-43.1	-37.6	170.3	178.5
2014-06-04 16:00	2014-06-12 22:00	276.9	-37.7	-35.0	173.3	176.3
1989-01-16 10:00	1989-01-28 17:00	157.9	-38.0	-35.2	173.7	175.8
1976-12-17 16:00	1976-12-25 03:00	244.3	-41.6	-38.2	172.7	178.3
2017-04-01 00:00	2017-04-06 16:00	423.9	-40.7	-37.7	173.9	176.8
1980-12-17 15:00	1980-12-30 16:00	143.7	-40.6	-37.2	175.6	178.5
1983-12-05 02:00	1983-12-14 20:00	260.6	-41.6	-34.6	172.5	177.0
1999-11-13 20:00	1999-11-20 17:00	239.2	-45.6	-44.5	167.6	169.5
2013-06-14 16:00	2013-06-23 03:00	195.7	-45.6	-43.2	170.2	173.0
1972-10-05 02:00	1972-10-10 09:00	307.2	-43.3	-35.2	171.1	174.1
1998-07-06 15:00	1998-07-12 00:00	385.5	-41.6	-35.1	172.5	176.9
1992-10-18 13:00	1992-10-25 02:00	211.8	-45.8	-36.5	167.6	175.5

1976-01-07 17:00	1976-01-17 08:00	127.4	-39.8	-34.6	172.8	175.8
2019-11-30 12:00	2019-12-08 21:00	415.2	-45.5	-42.2	167.6	171.8
1982-02-21 12:00	1982-03-03 22:00	163.6	-38.9	-36.7	175.0	177.0
1970-08-26 08:00	1970-09-01 16:00	471.6	-43.6	-39.2	170.8	174.2
1995-05-26 04:00	1995-06-04 01:00	312.3	-44.7	-35.7	169.5	175.2
2002-06-16 09:00	2002-06-21 08:00	231.9	-36.9	-35.1	173.2	175.7
2012-03-17 09:00	2012-03-22 20:00	196.0	-39.6	-34.6	172.8	176.9
1958-02-20 17:00	1958-02-25 10:00	253.1	-46.2	-36.8	167.7	176.1
1972-05-11 16:00	1972-05-18 10:00	199.0	-45.6	-38.0	170.0	175.2
2017-03-06 17:00	2017-03-13 12:00	236.5	-39.4	-36.6	174.1	176.8
1954-04-16 23:00	1954-04-21 09:00	174.0	-36.8	-34.6	172.8	175.5
1973-08-03 22:00	1973-08-08 16:00	251.6	-45.1	-38.9	170.4	177.9
2011-01-27 10:00	2011-01-29 06:00	306.7	-38.2	-35.3	173.6	176.1
1978-04-15 07:00	1978-04-23 07:00	194.1	-44.1	-39.2	171.2	175.1
2011-01-20 18:00	2011-01-24 06:00	333.7	-39.4	-35.2	173.1	176.1
2015-06-17 01:00	2015-06-20 21:00	414.8	-43.7	-39.1	170.9	175.6
1994-11-04 05:00	1994-11-10 12:00	311.0	-44.0	-39.2	170.1	175.7

Appendix E - Index PMP verification (all durations)

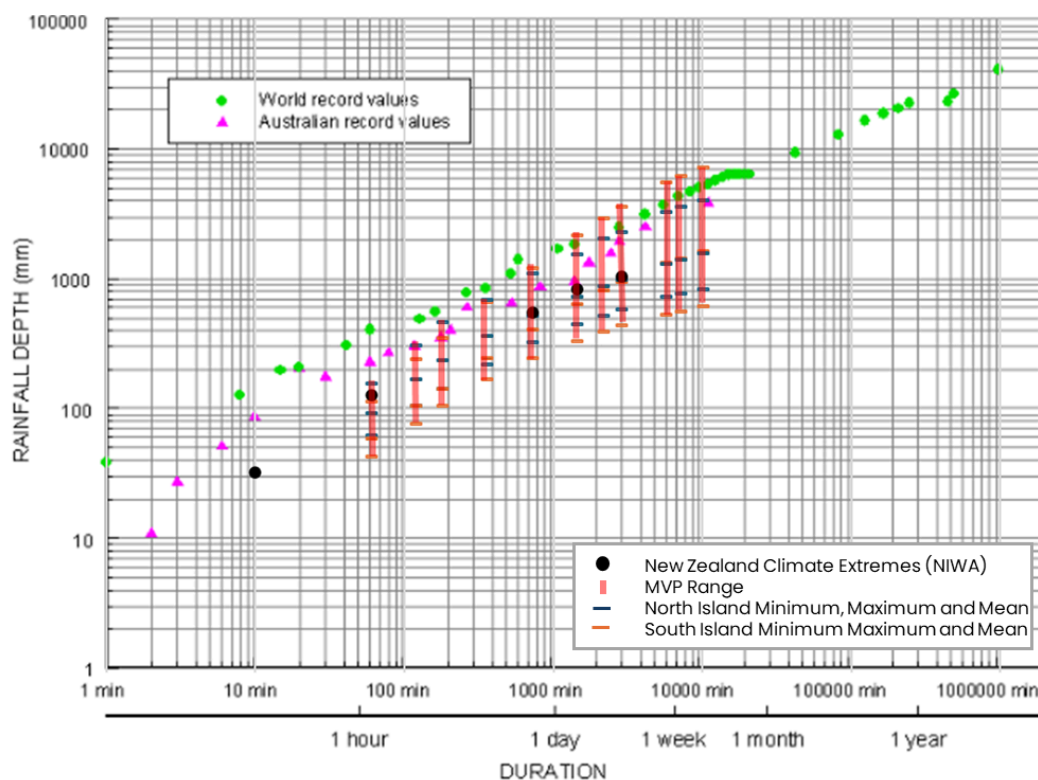


Figure E-1: MVP Index PMP estimates, and New Zealand's highest gauge precipitation depths (New Zealand Climate Extremes), overplotted on Australian and World record gauge precipitation depths (figure sourced from the Australian Government Bureau of Meteorology).