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The precipitation distribution across Westland Tai Poutini National Park

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Abstract

A 1981–2010 average annual precipitation distribution has been prepared for Westland Tai Poutini National Park using a combination of new and historic precipitation observations. The distribution was prepared using a repeatable objective interpolation of observed precipitation and is able to be updated as new precipitation observations are made. With inclusion of undercatch assessments, the distribution indicates mean annual precipitation from 3500 mm at the windward western coast to over 10000 mm in the centre of the region. The area of the highest precipitation does not relate to any obvious topographic attribute such as elevation or the distance to an orographic boundary. No consistent cross-mountain precipitation profile was able to be determined from the observations with variations attributed to the different ridge and valley orientations that influence where precipitation falls to the ground. The new distribution gives a region-wide 1981–2010 mean annual precipitation of 6200 mm. The estimated precipitation at the Main Divide, along the eastern edge of the region, does not align with that previously assessed for the region immediately to the east (the Lake Pukaki catchment and Aoraki/Mt Cook National Park). This indicates there may be a discontinuity in the precipitation distribution across the Main Divide in this area.

Keywords

rainfall, precipitation, orographic, mountains, New Zealand, Southern Alps

Introduction

The West Coast of the South Island, New Zealand has long been regarded as the wettest region of the country (Kidson, 1932). Rain gauge records have confirmed this with internationally extreme values observed in the headwaters of the Hokitika catchment (Griffiths and McSaveney, 1983a; Henderson and Thompson, 1999). Early attempts to plot the distribution of precipitation in the area (e.g., Kidson, 1929; Seelye, 1945; NZMS, 1975a) relied on expert judgement in lieu of rain gauge records for much of the mountain areas (Hessel, 1982). The largest isohyet on both the Kidson (1929) and Seelye (1945) precipitation maps estimated 5 m of annual rain for the western portion of the Southern Alps, while the later NZMS (1975a) map adjusted this estimate to 8000 mm, a 60% increase. Unfortunately, despite the increase, when tested in hydrological applications, the Southern Alps portion of this map proved inconsistent with stream flow records (Stephen, 1972; Jowett and Thompson, 1977). In an attempt to resolve this disparity a concerted effort to increase Southern Alps precipitation observations was carried out from 1976 focusing on a transect encompassing the Rakaia and Hokitika catchments (McSaveney *et al.*, 1978). The new observations proved the existence of a very strong horizontal precipitation gradient with measured amounts that indicated mean annual precipitation magnitudes of up to 12,000 mm, and found that the precipitation peak was well to the west of the topographic divide (Chinn, 1979). This, in turn, led to more refined precipitation maps being produced for the Cropp River (Griffiths and McSaveney, 1983b), the Hokitika catchment (Duncan, 1992) and the Hokitika – Wanganui region (Whitehouse *et al.*, 1983). The rain gauging effort coincided with a new national precipitation map (NZMS, 1985a) which included mean annual precipitation estimates from the new gauges but still relied on expert judgement for much of the remainder of the Southern Alps. The estimates for the mountains of Westland Tai Poutini were now mapped to be within a 9600 mm isohyet with a 12,800 mm isohyet located over the neves of the Fox and Franz Josef Glaciers. This represented a further 60% increase from the previous national precipitation map (NZMS, 1975a). Hydrological analysis found the mapped precipitation for the Southern Alps catchments were still in error, leading to the generation of a precipitation bias correction map (Woods *et al.*, 2006) to balance the water budget. The national precipitation map combined with the bias correction was then able to be used in hydrological modelling studies (e.g., Poyck *et al.*, 2011).

Short-circuiting the requirement for hydrological correction, Horrell (1990) mapped the precipitation distribution for South Westland by ensuring the observation-derived mean annual catchment precipitation balanced the water budget where streamflow records were available, a similar method to that used by Jowett and Thompson (1977) for the Upper Clutha catchment on the eastern side of the Southern Alps. A notable gap in the Horrell (1990) map is the Westland Tai Poutini National Park region where the lack of stream flow records and heavy glaciation made estimating the precipitation distribution uncertain (G. Horrell, pers. comm.). While ensuring the precipitation balanced the water budget for the gauged catchments, the map still relied on expert judgement to describe the precipitation distribution within each catchment.

Consideration of the hydrological water balance was also used in preparing a precipitation map of South Westland by Ruddell (1995). What makes Ruddell's map unique is that it is based on the glacial mass balance rather than stream water balance. Ruddell (1995) estimated the mean annual temperature at the long-term equilibrium elevation (the elevation at which glacier accumulation equals glacier melt) of all the Southern Alps glaciers from low elevation temperature records, then derived the mean annual melt, the mean annual solid precipitation and the mean annual ratio of solid precipitation to total precipitation at the equilibrium elevation, which provided the mean annual precipitation. The method produced mean annual precipitation estimates of 8000 mm at 1830 m elevation on the Fox neve and ~7400 mm at 1770 m elevation on the Franz Josef neve, with decreasing values to the east and increasing values to the west.

A more recent precipitation map for the region avoided the subjective expert judgement by guiding the interpolation using empirically-derived cross mountain profiles (Stuart, 2011). In a similar manner to the NZMS (1985a) precipitation map, Stuart mapped a precipitation peak of 10000 mm over the Fox and Franz Josef neves. Stuart (2011) used observations from the National Climate Database (NIWA, 2008) and NIWA's Water Resources Archive to prepare cross-mountain precipitation profiles, thereby updating the work of Henderson and Thompson (1999). This work was limited by the availability of observation data, much of which is not held in the two NIWA rainfall archives. The Stuart (2011) precipitation distribution has been used for glaciological studies (Anderson and Mackintosh, 2012) but to date there has been no comparison against stream flows. Cross-mountain profiles were first used to guide Southern Alps precipitation interpolation by Henderson (1992) when preparing a precipitation map for the Landsborough catchment, though this map also ensured catchment precipitation matched the water budget where stream flow records were available. Jowett *et al.* (1993) followed an almost identical procedure for the upper Waitaki catchment on the eastern side of the hydrological divide of the Southern Alps, though in their case they included a secondary empirically-derived elevation effect.

The application of precipitation distributions to hydrological studies has often circumvented the use of maps and directly utilised empirical relationships to terrain parameters, the most common being precipitation-elevation relationships (Kyriakidis *et al.*, 2001). In Westland Tai Poutini National Park such an approach has been applied to glaciological applications (e.g., Woo and Fitzharris, 1992; Oerlemans, 1997; Hooker and Fitzharris, 1999; Anderson *et al.*, 2006; Alexander *et al.*, 2011). An observation-based precipitation-elevation relationship was offered by Griffiths and McSaveney (1983a) which indicates a peak precipitation at the topographic divide of 18000 mm per year. An alternative fit to the same observed data was given by Woo and Fitzharris (1992) for the Franz Josef Glacier, with a reduced rate of precipitation increase above 1200 m, where they speculated that wind affects precipitation accumulation. Oerlemans (1997), again in application to the Franz Josef Glacier, also considered that the wind effects at elevation overcame the linear precipitation-elevation relationship observed at lower levels so that overall the precipitation-elevation relationship could be represented by a parabola, constraining it to 5000 mm per year at 0 m elevation and 10000 mm at 1250 m elevation based on observations, and dropping to 5000 mm at 2500 m elevation based on speculation. Anderson *et al.* (2006), continuing Franz Josef glaciological studies, also abandoned any attempt at a linear precipitation-elevation relationship but instead generated a polynomial to fit precipitation observations, this time augmented with snow accumulation observations for the upper elevations.

The precipitation observations for the Hokitika-Rakaia transect during the 1970s-80s indicated the best topographic predictor of precipitation magnitude was the upwind distance to the onset of the mountainous terrain, not elevation (McSaveney *et al.*, 1978; Chinn, 1979). This was later confirmed for the Haast and Milford regions of the Southern Alps as well (Henderson and Thompson, 1999), though they found that the magnitude of the precipitation peak varied and appeared to be related to the height of the Main Divide in the vicinity of the transect. Where there is a relationship between elevation and upwind distance, as there is on the Franz Josef Glacier, the precipitation-elevation relationship is the equivalent of a precipitation-upwind distance relationship. Difficulty arises when the elevation relationship is applied to a region where it does not relate to upwind distance, such as the general Westland Tai Poutini National Park region.

The problem of lack of precipitation data in the Westland Tai Poutini area has been attended to by various authorities. The Westland Catchment Board installed numerous storage gauges in the Whataroa catchment in the 1960s. These gauges were read intermittently when government workers (deer cullers) and recreationists (trampers and hunters) occasionally visited the sites. These data are now held by the West Coast Regional Council. The former Ministry of Works set up a transect of storage rain gauges from Okarito to the Franz Josef Glacier in 1982, which was soon augmented by a similar transect to the south from Gillespies Beach to Chancellor Hut in the Fox Glacier region. These transects were operated by the National Parks Board (the predecessor to the current Department of Conservation), which took over the administration of the southern (Fox) transect and continued operating it for 10 years. The Department of Conservation were further involved in rain gauge collection through maintaining manual sites at their offices in the Fox and Franz Josef townships since the 1960s, then later establishing and maintaining gauges at Welcome Flats Hut and at the terminus of the Fox Glacier in the 2000s, with the latter gauge intended to assist with estimation of rockfall hazard. Additional gauges have been installed at Welcome Flats by GNS Science, specifically to assist with investigating the effects of earthquakes on geothermal water temperatures, by Fox Glacier Guides at the Fox Terminus for their own information and by SAlpEx, a multi-agency investigation of Southern Alps weather and climate (Wratt *et al.*, 1996), with a temporary transect of automatic rain gauges in the Franz Josef region, this time extending up to Almer Hut overlooking the tongue of the Franz Josef Glacier. To assist with precipitation mapping and to better understand processes that affect precipitation distribution, nine rain gauges were installed in the region from March 2011 to April 2013.

The Westland Tai Poutini National Park is an area that is dominated by its high precipitation, which contributes to many of the park's glaciers reaching to low elevations (Anderson *et al.*, 2006) on which the local tourism depends (Purdie, 2013). High precipitation, along with high sediment input to the upstream catchments, is a contributing factor to the high risk of flooding in the town of Franz Josef (Westland District Council, 2008; Davies *et al.*, 2013). In addition, hazards associated with earthquakes in the region are exacerbated by the high rainfall (Robinson and Davies, 2013) and earthquake processes themselves are inextricably linked to groundwater water storage and flow derived from the high precipitation (Sims, 2013; Sutherland *et al.*, 2012). An improved understanding of the precipitation regime in the area is valuable through improved resource assessment, hydrological forecasting, hazard estimation and climate change effects analysis.

Immediate applications for improved understanding of precipitation distribution are in flood forecasting and rockfall hazard assessment. Longer term, estimates of climate variability on hydrology (flood frequency and glaciology), which are limited by the uncertainty of the current estimates of precipitation distribution, may be improved. In addition, the question of the effect of groundwater on the region's tectonic activity requires improved estimates of the precipitation input to progress (Sims, 2013).

This paper draws together available precipitation observations for the area to provide an improved description of its average annual distribution of precipitation. The next section provides a description of the Westland Tai Poutini National Park area. This is followed by a description of the precipitation data sources and the method used for preparing the 1981–2010 average annual precipitation totals and assessing gauge undercatch. The results are then given including a description and outcome of the interpolation method used to prepare the precipitation distribution map. The difference between the resulting precipitation distribution and three alternative distributions is then assessed.

Study site

The area of interest is largely within the Westland Tai Poutini National Park near the centre of the South Island of New Zealand at 170° 5' E, 43° 30' S (Fig. 1). It has a northern boundary of the Waiho catchment, a southern boundary of the Cook River catchment, the Main Divide of the Southern

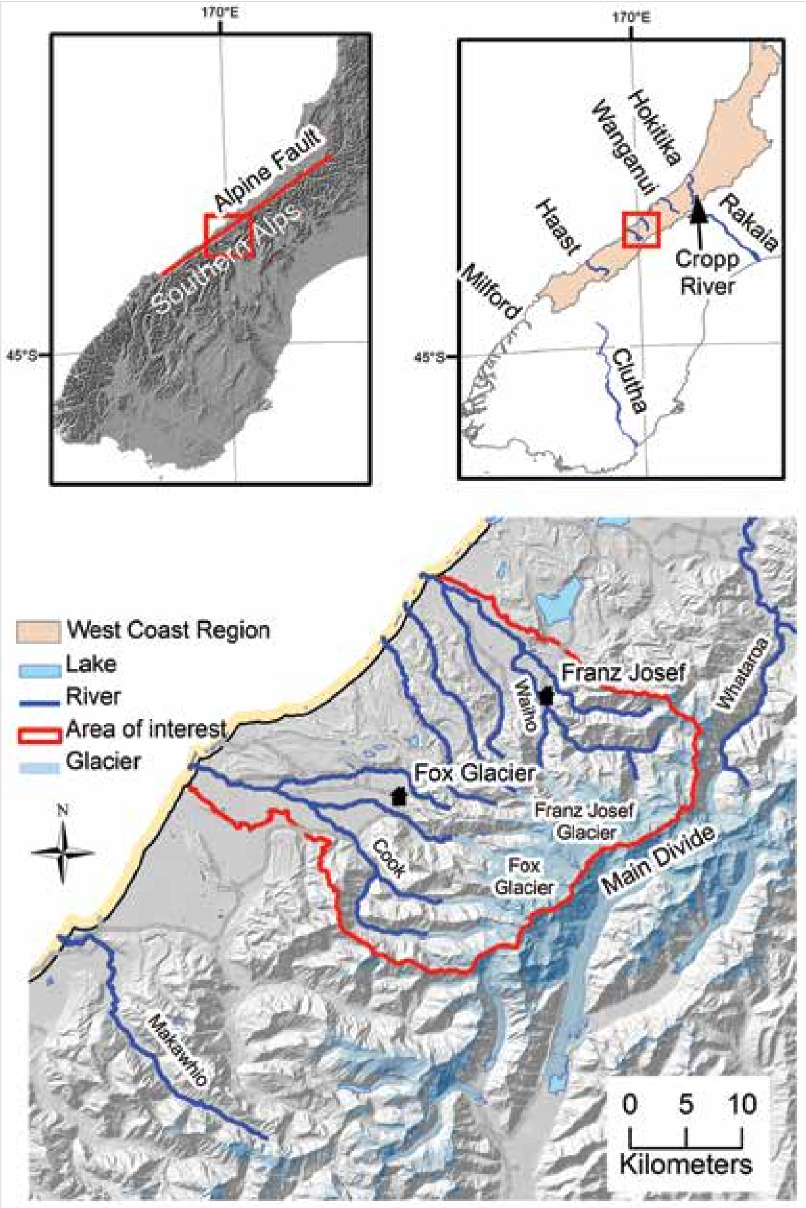

Figure 1 – Location of the Westland Tai Poutini National Park region showing rivers and geographical features mentioned in the text

Alps as its eastern boundary, and the Tasman Sea as its western boundary. The area is 880 km^2 with approximately 28 km from the coast to the Main Divide, and 31 km from the southern to the northern boundary. The elevation of the area averages 830 m, ranging from sea level up to 3487 m at Mt Tasman, New Zealand's second highest peak.

The upper area contains 68 glaciers, including New Zealand's third and fourth largest glaciers, Fox and Franz Josef glaciers, respectively (Chinn, 2001). The glaciers cover 146 km^2, or 16.5% of the area, the second largest landcover type within the study area. The dominant landcover is native forest (43%), with alpine gravel and rock the third largest landcover (10%) (Steve Thompson and Partners, N.D.).

The climate of the catchment is primarily influenced by its position within the Southern Hemisphere westerly wind belt, sandwiched between the temperate moisture source of the Tasman Sea and the climate barrier of the Southern Alps. High precipitation results from the inflow of saturated maritime air cooling as it progresses southeast over the Tasman Sea and condensing into wide areas of stratiform cloud which then interact with cyclonic systems and/or the Southern Alps (Hessel, 1982). Precipitation magnitude variation is caused by a complex relationship between the rate of vertical air lifting and the moisture content of that air. Highest precipitation regions on the West Coast are generally associated with areas immediately downwind of the onset of the first orographic barrier to the air, not with the highest elevations (McSaveney *et al.*, 1978; Henderson and Thompson, 1999). Temperatures vary throughout the study area according to altitude, with the mountain tops remaining below zero degrees Celsius for the majority of the year. The lower regions are strongly tempered by the sea surface temperatures that range, on average, from 12°C to 17°C (Uddstrom and Oien, 1999) with Franz Josef township's mean annual temperature being 11°C (Hessel ,1982). Snow can fall in the higher regions at any time of the year but accumulation of snow from one storm to another is more common in the winter months from April until October. This climate has resulted in seasonal snow and perennial ice being important components of the area's hydrology.

Data sources

Rainfall gauge site names, dates of operation, gauge type and data sources are listed in Table 1. Included are nine gauges temporarily (2011–2013) installed as part of this research in locations that were identified as likely to receive high precipitation but were previously un-sampled. Some of the data obtained covered long periods, while some gauges were installed for barely a year (Fig. 2). The locations of the precipitation measurement sites are irregularly spread across the region focussed around the Franz Josef and Fox townships (Fig. 3). In total 57 precipitation gauges were identified for 52 sites (sometimes multiple gauges operated at the same site) with data obtained for 51 gauges from 47 of the sites. Six gauges were known to have been installed, but no data were obtained.

The decision was made not to include snow information previously collected in the neves from crevasse stratigraphy measurements (Ruddell, 1995; Anderson *et al.*, 2006; Purdie *et al.*, 2011a) and radar measurements (Kees, 2011), though daily snow accumulation measurements have been included (Purdie *et al.*, 2011b). Crevasse stratigraphy involves measuring the depth of snow from a glacier surface to a discoloured line in the snow observed in the side of a crevasse, interpreted as the glacier surface of the previous summer. Converting snow accumulation measurements from crevasse stratigraphy into mean annual precipitation

Table 1 – Precipitation gauges within the catchment. The data source 'NIWA, 2008' is the National Climate Database, available online to the general public, whereas 'NIWA' indicates the data is available from NIWA upon request. WCRC is the West Coast Regional Council and DOC is the Department of Conservation.

Index	Name	Type	Start	Finish	Data Source
1	Okarito	Manual daily gauge	1/10/1981	Current	(NIWA, 2008)
2	Okarito at Wahapo	Tipping spoon	2/05/2000	Current	NIWA
3	Forks	Storage gauge	27/06/1980	10/01/1983	(Henderson, 2010)
4	Okarito	Manual daily gauge	1/02/1935	1/08/1945	NIWA
5	McDonalds	Storage gauge	28/04/1981	10/01/1983	NIWA
6	Waitangi-Taona	Cassela Weekly	1/05/1968	Unknown	Site info in NWASCO (1969), no observed data found
7	Lake Mapourika	Cassela Weekly	1/08/1962	Unknown	Site info in NIWA (2008), no observed data found
8	Potters Creek	Cassela Weekly	1/08/1962	1/01/1978	(NZMS, 1966a; Walter, 2000; NIWA, 2008)
9	Potters Creek	Daily manual	1/12/1983	31/01/1987	WCRC
10	Franz Josef Ews	Tipping Bucket	30/05/2003	Current	(NIWA, 2008)
11	Gunn	Storage gauge	26/03/1965	19/11/1970	(SCRCC, 1966), WCRC
12	Franz Josef T.H.C.	Manual daily gauge	1/11/1926	1/10/1983	(NIWA, 2008)
13	Franz Josef Park HQ	Storage gauge	11/10/1982	8/11/1982	NIWA
14	Waiho @ SH6, WCRC	Tipping Bucket	24/06/2009	Current	WCRC
15	Franz Josef	Manual daily gauge	1/07/1978	Current	(NIWA, 2008)
16	Deadmans	Storage gauge	27/06/1980	8/03/1982	(Henderson, 2010)
17	Gillespies Beach	Storage gauge	2/09/1981	4/01/1983	(Henderson, 2010)
18	Gillespies Beach	Manual daily gauge	1/03/1959	1/07/1971	NIWA
19	Butler Junction	Storage gauge	20/03/1965	4/01/1970	WCRC
20	Butler Hut	Storage gauge	20/03/1965	1/12/1973	(NIWA, 2008)(NWASCO, 1969) WCRC
21	Alex Knob - mid	Storage gauge	23/03/1982	30/12/1982	(Henderson, 2010)
22	Douglas	Storage gauge	27/06/1980	10/01/1983	(Henderson, 2010)
23	Douglas Hut	tipping bucket	1/01/1984	Current	NIWA
24	Lower Callery	Tipping bucket	10/03/2011	18/03/2013	This study
25	Sentinel Rock	Storage gauge	27/06/1980	10/01/1983	(Henderson, 2010)
26	Alex Knob - top	Storage gauge	26/08/1982	30/12/1982	(Henderson, 2010)
27	Alex Knob	Tipping bucket	1/09/1991	1/12/1995	NIWA
28	Upper Callery	Tipping bucket	10/03/2011	5/11/2012	This study
29	Lower Spencer	Tipping bucket	10/03/2011	7/05/2013	This study
30	Franz 1967 Terminus	Storage gauge	27/06/1980	10/01/1983	(Henderson, 2010)
31	Franz 1978 Terminus	Storage gauge	13/11/1980	2/03/1982	(Henderson, 2010)
32	Plane table	Storage gauge	2/09/1981	4/01/1983	(Henderson, 2010)
33	Upper Spencer	Tipping bucket	10/03/2011	12/04/2013	This study
34	Luncheon Rock	Tipping Bucket	1/09/1982	1/12/1986	NIWA
35	Luncheon Rock	Storage gauge	5/01/1982	31/12/1982	NIWA
36	Fox-Park HQ	Manual daily gauge	1/01/1965	31/12/1990	DOC
37	Fox Glacier,Main Rd	Manual daily gauge	1/07/1964	1/03/1994	(NIWA, 2008)
38	Fox Glacier M.W.D.	Manual daily gauge	1/04/1928	1/06/1988	(NIWA, 2008)
39	Almer	Tipping Bucket	1/10/1991	1/02/1996	NIWA
40	Tip	Storage gauge	2/12/1981	4/01/1983	(Henderson, 2010)
41	Bluff	Storage gauge	2/09/1981	4/01/1983	(Henderson, 2010)
42	Hummocks	Storage gauge	2/09/1981	4/01/1983	(Henderson, 2010)
43	Fox Glacier terminus carpark	Manual daily gauge	3/03/2009	Current	DOC
44	Fox lateral moraine	Storage gauge	2/09/1981	4/01/1983	(Henderson, 2010)
45	Fox glacier terminus	Manual daily gauge	1/01/2010	Current	Alpine Guides Fox Glacier Ltd.
46	Centennial Hut	Snow board	14/07/2008	7/08/2008	(Purdie *et al.*, 2011b)
47	Chancellor hut	Storage gauge	18/03/1982	9/12/1982	(Henderson, 2010)
48	Lower Boyd	Tipping bucket	10/03/2011	7/05/2013	This study
49	Upper Boyd	Tipping bucket	1/06/2011	7/05/2013	This study
50	Karangarua	Manual daily gauge	1/01/1935	1/07/1961	(NIWA, 2008)
51	Lower Balfour	Tipping bucket	3/09/2011	5/11/2012	This study
52	Upper Balfour	Tipping bucket	1/06/2011	7/05/2013	This study
53	La Perouse	Tipping bucket	9/02/2012	7/05/2013	This study
54	Welcome Flats-DOC	Manual daily gauge	11/11/2008	1/01/2014	DOC
55	Welcome Flats-GNS	Tipping bucket	8/03/2009	1/01/2014	Simon Cox,GNS Science

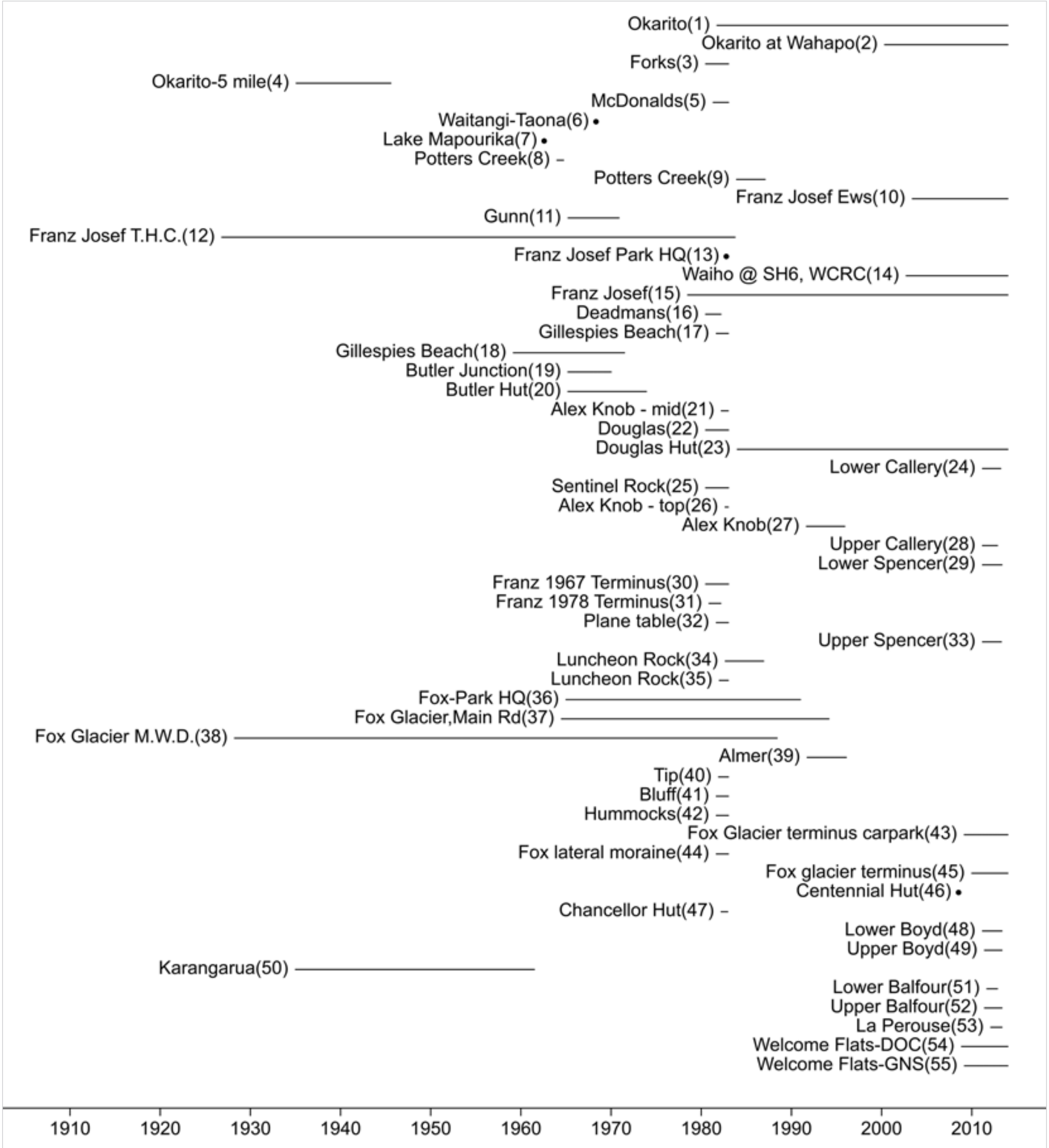

Figure 2 – Operation dates of rain gauges within the study region

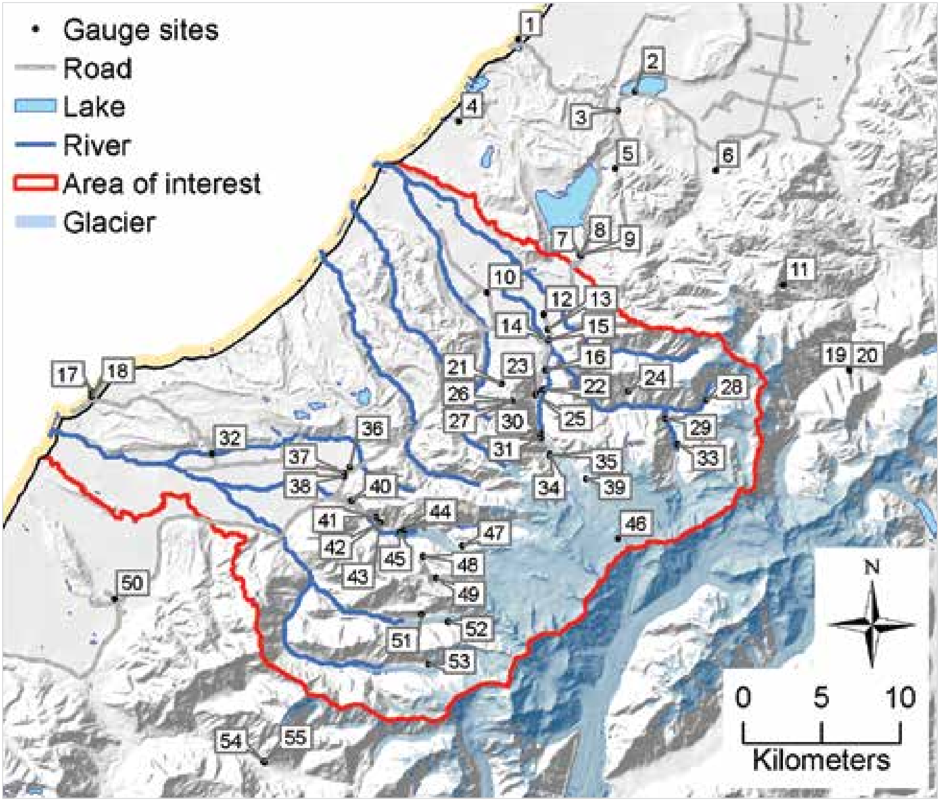

Figure 3 – Locations of precipitation measurement sites that have operated at some time in the region. Site references are given in Table 1.

requires estimates of melt and wind re-distribution, not insignificant problems. Conversion of radar two-way travel times to snow water equivalent requires knowledge of the snow density to snow depth relationship and unequivocal identification of previous summer layers from the radar trace, both of which introduce considerable uncertainty to the estimation of mean annual precipitation.

Average annual precipitation and undercatch assessment methods

Long-term averages of precipitation measurements provide an index of a location's climate. These, in turn, can be used for comparison to other locations and other time periods or for prediction of future conditions for planning and risk assessment (Guttman, 1989). To ensure international compatibility of long-term averages the World Meteorological Organisation recommends the use of 30-year average annual precipitation totals, for which they give the name 'rainfall normal' (WMO, 1983). For comparison with normals prepared in other regions, the 30-year period starts with the first year of a decade. Ideally the normals utilise data recorded from the entire 30 years under consideration. Thirty-year normals have been published for various precipitation gauge sites in the region, as shown in Table 2.

Table 2 – Published precipitation normals (mm) for gauge sites in the region

Index	Site	1921-1950	1941-1970	1951-1980
37	Fox Glacier, Main road		4769	4548
38	Fox Glacier, MWD	4773	4780	4586
12	Franz Josef THC	5070	5130	4950
4	Okarito		3200	
18	Gillespies Beach		3100	2977
50	Karangarua		3846	3674
16	Deadmans		7583	
22	Douglas		6567	
25	Sentinel Rock		7021	
30	Franz Terminal 1		8469	
31	Franz Terminal 2		8670	
34,35	Luncheon Rock		10565	

Sources: (NZMS, 1966b), (NZMS, 1973; NZMS, 1975b; Griffiths and McSaveney, 1983a), (NZMS, 1985b)

Where a 30-year record is unavailable, an estimate of the normal may be generated through correlation with a long-term site. Analysis of relationships between gauge site data and long-term gauge site data found the highest correlations were most commonly with the Franz Josef daily manual gauge site data. To ensure correlations were against a stable set of observations, homogeneity tests of the Franz Josef daily manual (site 15) precipitation record were carried out following Rhoades and Salinger (1993). This involved comparing the plots of the cumulative sum of monthly precipitation total anomalies for gauge sites in the region. Plots with slope breaks that were site specific indicate an inhomogeneity caused by site changes, whereas slope breaks common to multiple sites indicate climate effects. The tests indicated the precipitation record from the Franz Josef daily manual site (site 15) for the 30-year period from 1981 to 2010 is free of catch-affecting site changes. This period was selected for estimating a set of precipitation normals for all gauge sites within the study area.

Further homogeneity tests for all daily sites with longer than 25 years of record were carried out. This analysis showed that no major inhomogeneities existed in these sites, ensuring their suitability for preparation of precipitation normals.

Where observations for the complete 30-year period were not available, or existed only outside the 30-year period, an estimation of the climate normal was prepared through consideration of statistical relationships between sites following Kerr *et al.* (2011). This method requires identifying a statistically significant correlation of log (base 10) values of pseudo-monthly (multi-week periods with at least two rain events) precipitation between a site of interest, and a site for which a normal estimate has already been obtained.

An estimate of the log of the precipitation total for the average period length at the site of interest may then be found using:

$$log(yA_f) = mlog(xA_f) + c \qquad (1)$$

Where y is the average of the precipitation depth totals measured during the pseudo-monthly time periods at the site of interest, m is the slope of the regression line between measurement period log totals at the site of interest and the reference site, x is the average of the precipitation depth totals at the reference site for the same pseudo-monthly time periods that observations were obtained at the site of interest, c is the offset of the regression line, and A_f is the average measurement period as a fraction of a year.

The average annual precipitation total (y) may then be established using:

$$y = \frac{10^{mlog(xA_f)+c}}{A_f} \qquad (2)$$

Where possible, the reference site used was one of the Franz Josef gauge sites: Franz Josef THC (site 12) for sites that operated between 1926 and 1980, Franz Josef (site 15) for sites that operated between 1980 and 2004, and Franz Josef EWS (site 10) for sites that operated from 2004. Overlapping records between these three sites enabled correlations to be established and 1981–2010 normal estimates to be derived from the Franz Josef (site 15) gauge.

Average annual precipitation uncertainty and undercatch

The methods used to observe the precipitation and to calculate the 30-year average annual precipitation affect the uncertainty of the resulting mean annual precipitation estimates. Tipping bucket gauges undercatch as a result of the finite time required for a tip to occur (WMO, 2008). This undercatch increases as the precipitation intensity increases and has been measured at over 25% for extreme (> 150 mm hr^{-1}) intensities (Humphrey *et al.*, 1997). This error is partly overcome through dynamic calibration for a large number of bucket tips at a known intensity. The NIWA tipping bucket gauges and the nine gauges installed as part of this study were dynamically calibrated within 3% (Fenwick, 2008) thereby accounting for tipping bucket delays and wetting errors. The automatic gauges without a known calibration were assigned an arbitrary 3% measurement uncertainty. For daily gauges a wetting undercatch has been found to equal a loss of 0.1 mm per precipitation event (Austin, 1939). Assuming one event per precipitation day and with an average amount on a precipitation day being always greater than 20 mm, the wetting undercatch was less than 1% and so was ignored.

Where wind and temperature data were available (at the Franz Josef EWS and the gauges installed for this study) the wind-induced undercatch was calculated following Yang *et al.* (1998). For sites without temperature and windspeed data and for storage gauges, wind-induced undercatch was allocated subjectively based on nearby or similar sites accounting for the site elevation, average annual precipitation, and orifice height.

For most of the storage gauges no evaporation estimate was made, as the standard technique for storage gauges is to add an anti-evaporation oil barrier to gauge contents.

For those sites with normals derived from correlation, the 95% confidence limits may be calculated from the standard deviation (*s*) and number (*n*) of samples:

$$CL(0.95) = 2\frac{s}{\sqrt{n}} \qquad (3)$$

In this case, the samples are the residuals between the determined regression line and the log of the observed pseudo-monthly values. By doing this in log space, the upper confidence limit was greater than the lower confidence limit when transformed back to precipitation depth. The estimated normal was then adjusted up to be in the centre of the two confidence limits.

Table 3 lists the estimated total undercatch for each gauge. The undercatch was applied as an offset to provide the normals shown in Table 3. The uncertainty presented in Table 3 is a combination of the gauge measurement uncertainty and correlation confidence limits.

Interpolation

A precipitation map can be prepared from precipitation observations in a number of ways including area averaging, Thiessen polygons (Thiessen, 1911), Inverse Distance Weighting, isohyet generation, spline interpolation (Hutchinson, 1995) and Kriging (for a review see Goovaerts, 2000).

Most average annual precipitation maps previously produced in New Zealand (Kidson, 1929; Seelye, 1945; NZMS, 1975a; NZMS, 1985a; Horrell, 1990) have used subjective analysis by climate experts to determine the values at non-measured locations. This has been done by drawing

Table 3 – Reference sites, correlations (*not significant at the 0.9 level), number of measurement periods used in preparing the correlations, estimated gauge undercatch and estimated 1981–2010 precipitation normals adjusted for undercatch. Where no correlations are given the normal is estimated from a ratio of totals.

Index	Name	Reference gauge	Correlation	No. of periods	Undercatch (%)	1981–2010 normal (mm)
1	Okarito	Franz Josef	0.86	252	7	3486 +/- 70
3	Forks	Franz_THC	0.73	31	7	4529 +/- 317
4	Okarito-5 mile	Franz_THC	0.81	41	7	3547 +/- 106
5	McDonalds	Franz_THC	0.52	21	7	4998 +/- 500
8	Potters Creek	Franz_THC		1	7	6189 +/- 1238
9	Potters Creek	Franz Josef	0.9	10	7	4975 +/- 298
10	Franz Josef Ews	Franz Josef	0.819	97	7	4754 +/- 143
11	Gunn	Franz_THC	0.919	21	10	11391 +/- 797
12	Franz Josef T.H.C.	Franz Josef	0.95	21	4	5698 +/- 456
13	Franz Josef Park HQ	Franz Josef		1	4	5913 +/- 1183
14	Waiho @ SH6, WCRC	Franz_Josef	0.73	49	8	7239 +/- 362
15	Franz Josef	Franz Josef		191	5	6059 +/- 0
16	Deadmans	Franz_THC	0.688	18	8	6564 +/- 459
17	Gillespies Beach	Franz_THC	0.71	14	8	3327 +/- 233
18	Gillespies Beach	Franz_THC	0.79	42	7	3462 +/- 208
19	Butler Junction	Franz_THC		1	4	7951 +/- 1590
20	Butler Hut	Franz_THC	0.67 *	23	4	5849 +/- 702
21	Alex Knob – mid	Franz_THC		1	4	8914 +/- 2674
22	Douglas	Franz_THC	0.766	31	4	6797 +/- 408
23	Douglas Hut	Franz_Josef	0.85	247	4	7322 +/- 146
24	Lower Callery	Franz_EWS	0.604	17	4	6879 +/- 275
25	Sentinel Rock	Franz_THC	0.771	31	7	7659 +/- 460
26	Alex Knob - top	Franz_THC		1	6	5302 +/- 1591
27	Alex Knob	Franz _Josef	0.91	37	6	8343 +/- 250
28	Upper Callery	Franz_EWS	0.67	16	5	7845 +/- 549
29	Lower Spencer	Franz_EWS	0.84	22	4	7861 +/- 393
30	Franz 1967 Terminus	Franz_THC	0.78	31	7	9315 +/- 559
31	Franz 1978 Terminus	Franz_THC	0.66	15	7	9141 +/- 914
32	Plane table	Franz_THC	0.64	14	7	4376 +/- 438
33	Upper Spencer	Franz_EWS	0.67	16	5	8830 +/- 1060
34	Luncheon Rock	Franz_Josef	0.9	36	7	11029 +/- 331
35	Luncheon Rock	Franz_THC	0.66	11	7	12514 +/- 1502
36	Fox-Park HQ	Franz_THC	0.91	174	3	5270 +/- 105
37	Fox Glacier,Main Rd	Franz_Josef	0.92	132	4	5158 +/- 103
38	Fox Glacier M.W.D.	Franz_THC	0.88	252	4	5199 +/- 104
39	Almer	Franz_Josef	0.83	23	12	9116 +/- 547
40	Tip	Franz_THC	0.93*	13	5	6031 +/- 241
41	Bluff	Franz_THC	0.78*	14	5	5743 +/- 287
42	Hummocks	Franz_THC	0.78*	16	5	6437 +/- 386
43	Fox terminus carpark	Franz_Josef	0.95	19	5	6205 +/- 310
44	Fox lateral moraine	Franz_THC	0.6	9	7	7382 +/- 369
46	Centennial Hut	Franz EWS		1	10	6919 +/- 2076
47	Chancellor Hut	Franz_THC		1	10	9549 +/- 1910
48	Lower Boyd	Franz_EWS	0.71	16	6	7920 +/- 475
49	Upper Boyd	Lower Boyd	0.55	15	5	7597 +/- 684
50	Karangarua	Franz_THC	0.86	145	7	4290 +/- 86
51	Lower Balfour	Franz_EWS	0.82	12	7	8206 +/- 903
52	Upper Balfour	Lower Balfour	0.9*	8	7	8682 +/- 260
53	La Perouse	Upper Balfour	0.78*	7	7	7188 +/- 1078
54	Welcome Flats-DOC	Franz_Josef	0.85	15	4	7410 +/- 445
55	Welcome Flats-GNS	Franz_Josef	0.79*	10	4	6212 +/- 621

isohyets to align with the site precipitation estimates in a manner that is in keeping with the expert's understanding of precipitation distribution. In contrast, objective methods enable the interpolation to be recreated given the specific methods and controlling parameters, and are explicit in the additional factors considered. For this study, an objective method was used whereby the region was split into two, the area to the west (windward with respect to the predominant westerlies) of the Alpine Fault and the area to the east, reflecting the sharp transition in terrain complexity and associated change in precipitation variability. Division of precipitation interpolation methodologies based on terrain complexity has been shown to lead to improved precipitation surfaces (Kumari *et al.*, 2017). The western region was interpolated using Local Polynomial Interpolation, which interpolates to a point by fitting a polynomial (in this case first order) to the measured values within a prescribed local area around the point, with the weighting of measured values described by a kernel function. This method enabled interpolation to be restricted to only the local areas that have a similar distance to the sea, as this was considered the primary control on the precipitation distribution for the areas west of the Alpine Fault. For each point, the local area was described by an ellipse 200 km long, 5 km wide and angled at 54° to align with the Alpine Fault. A minimum of five sites were required to enable the interpolation, and a maximum of 10. An exponential weighting kernel, implemented in ArcGIS™ 10.0, was found, through trial and error, to provide a surface that was considered reasonable. The output cell size was set to 1 km^2.

The selection of local polynomial interpolation and its controlling parameters was subjective based on what looked 'reasonable'and used available site information in a manner that matched current understanding of precipitation distribution controls. Alternative techniques may have produced an equally 'reasonable' precipitation surface. Although the selection of the method was subjective, the application of the method is objective, and able to be repeated. In this way, the resulting precipitation map differs from manually-drawn isohyetal maps (e.g., NZMS, 1985a) that are non-repeatable and present challenges for updating as new or corrected site information becomes available.

Prior to interpolating the eastern region, the interpolated western precipitation distribution was sampled at 2.5 km intervals along the Alpine Fault. These points were added to the eastern region sites to be used, ensuring a level of constraint at its western boundary. The eastern region was interpolated using Ordinary Kriging, as Kerr *et al.* (2011) used for the nearby Lake Pukaki catchment, using an exponential variogram and a maximum of five sites per interpolation point. As with the western region, the selection of the interpolation technique was subjective and based on the results looking 'reasonable'. Kriging has the advantage of not being constrained to any particular site value and manages the interpolation weighting based on observed inter-site variance, rather than selected *a priori* or through manual tuning. As with the western region, an attempt was made to provide an interpolation technique that was as objective as possible whilst acknowledging that the selection of the technique, and its parameters, was subjective. Using different interpolation techniques in different areas enables the advantages of each to be maximised and provides a pragmatic approach when any one single technique is unlikely to be optimal for regions of different gauge density, precipitation variability and spatial precipitation trends.

The two regions were blended by averaging in a transition area from the Alpine Fault to 2 km to the east. The resultant surface was contoured at 1000 mm intervals, the contours smoothed, and contours of less than

5 km length removed. The resulting isohyetal map is shown in Figure 4. The mapped precipitation increases from about 3500 mm at the coast to about 6000 mm at the Alpine Fault. Eastward of the Alpine Fault the distribution becomes more complicated and no simple relationship with the terrain is apparent. The map shows how the high precipitation observed at Luncheon Rock (sites 34 and 35) are not observed to the north by the gauge in the Callery Valley (site 24), or to the south by the gauges in the Fox, Balfour or La Perouse valleys (sites 47, 48, 49, 51).

Comparison with alternative precipitation distributions

The estimated mean annual precipitation surface was compared to a 1 km resolution NZMS 1950–1981 normal map (NZMS, 1985a), a one-year (April 2009 to March 2010) climatology map prepared from 12 km resolution NZLAM forecast model output (Webster *et al.*, 2008) resampled (using a spline interpolation) to 10 km, and the 5 km resolution Stuart (2011) distribution for the region. In each case the 1981–2010 precipitation map prepared in this study was resampled to match the resolution of the comparison surface. In addition, the maps were scaled so that the grid square that contained Franz Josef EWS matched the 1981–2010 map's grid square estimate. The difference between the 1981–2010 distribution and each of the three other distributions is shown in Figure 5.

The NZLAM map has precipitation values much lower than the 1981–2010 surface in the mountain regions. This is likely to be related to topography resolution of NZLAM's underlying model, which operates at 12 km, so that much of the higher ridge lines are averaged to a lower elevation. Because the NZLAM output shows lower precipitation than observed in the mountain regions it will leave greater moisture in the atmosphere downwind of the Southern Alps, which will affect estimated precipitation and associated variables in the Canterbury region. Where NZLAM output is used for hydrological modelling it will not provide enough water for the west coast catchments, leading to flows being underestimated. The underestimation of precipitation by the NZLAM model output is consistent with the findings of Webster *et al.* (2008), whereby model resolutions of 4 km or finer were required to obtain precipitation accumulations consistent with observations, though notably their assessment used VCSN data which is itself strongly biased by its interpolation. VCSN is guided by the NZMS 1951–1980 precipitation map (Tait *et al.*, 2006), which, as discussed below, is in disagreement with the new observed precipitation distribution presented here.

In contrast to the NZLAM distribution, the Stuart (2011) precipitation distribution overestimates precipitation in the mountain areas. The Stuart (2011) distribution used observations east of the Alpine Fault that were limited to a subset of the Waiho gauges (sites 23, 27, 34) and assumed the cross-mountain precipitation distribution in this region was well described by these observations. The new observations in the Callery, Spencer, Balfour and La Perouse (sites 24, 28-29, 33, 51-53) indicate that a single cross-mountain precipitation profile is inappropriate for this region. The NZMS 1951–1980 distribution also overestimates the precipitation in the mountain areas, to a greater degree than the Stuart (2011) distribution, due to a lack of observations when the map was prepared. Both the Stuart (2011) and NZMS 1951–1980 distributions will lead to overestimated flow if they are used as input to hydrological models.

An alternative way to compare the different surfaces is by mean annual catchment precipitation. This was done for the Callery,

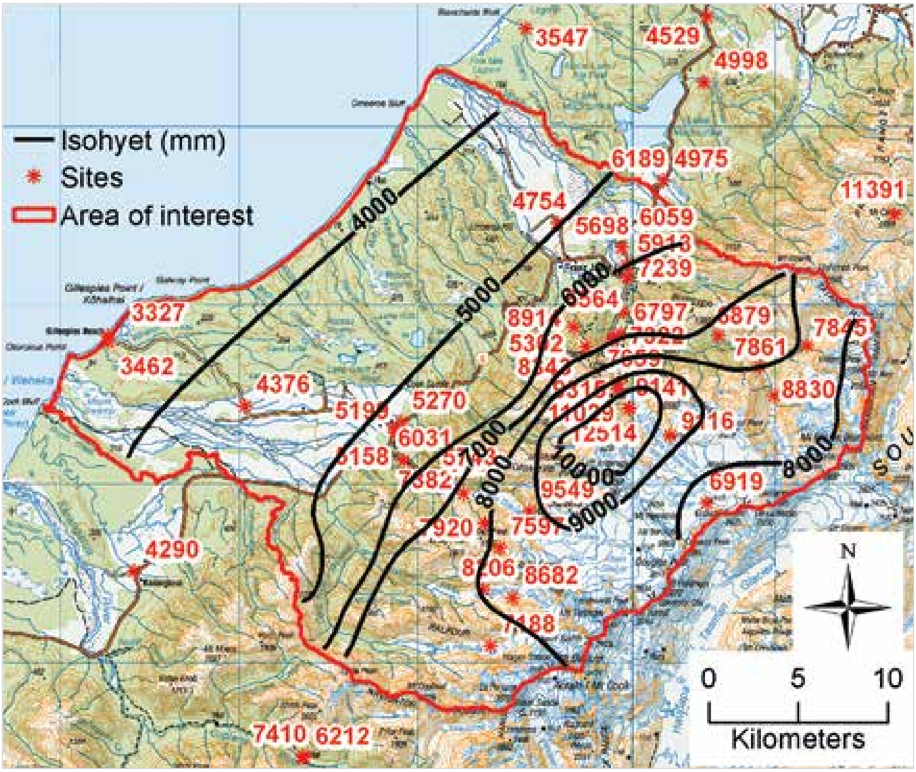

Figure 4 – Mean annual precipitation for 1981-2010. Isohyets are in mm. Red values are 1981-2010 mean annual precipitation estimates for the gauge sites. Background image is LINZ Topo250 topographic maps.

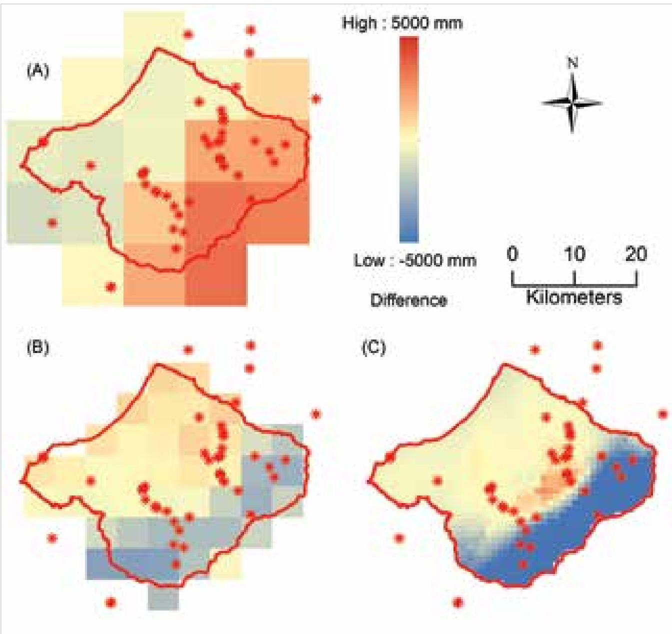

Figure 5 – Difference between the 1981-2010 mean annual precipitation distribution and: the NZLAM (Webster *et al.*, 2008) 2009-2010 precipitation totals (A), the Stuart (2011) precipitation distribution (B), and the NZMS 1951-1980 rainfall map (NZMS, 1985a) (C). Positive (negative) values indicate the 1981-2010 precipitation is higher (lower) than the distribution being compared. Asterisks represent the observation sites. Red line gives the region outline as per Figure 1.

Waiho, Fox and Cook rivers (Table 4). The NZLAM and Stuart (2011) distributions were resampled to 1 km resolution using bilinear interpolation prior to calculating the catchment values so that all distributions were at the same resolution.

Table 4 – Mean annual catchment precipitation (mm) derived using four different rainfall distributions, for four catchments within the Westland Tai Poutini National Park

Catchment	1981-2010 (this study)	NZLAM	Stuart (2011)	NZMS 1951-80
Callery	7976	5686	11459	13650
Waiho	8612	5606	10990	12451
Fox	8249	5496	11193	12200
Cook	7075	5563	10941	12231

The nearest river flow measurement sites with which to compare the mean annual catchment precipitation totals in Table 4 are the Whataroa and Makawhio catchments, adjacent to the study region (see Fig. 1). Their flow data indicate mean annual precipitation (mean annual flow plus evapotranspiration) of 10000 mm and 8600 mm, respectively. These flow-based estimates assume no mean annual change in water storage, no groundwater flow around the flow measuring site and evapotranspiration equivalent to the 600 mm potential evapotranspiration calculated from the 2004 to 2016 climate observations at the Franz Josef electronic weather station. Assuming these flow-based estimates are representative of what occurs within the neighbouring Westland Tai Poutini National Park region, then of the four distributions, the 1981–2010 distribution provides the closest estimate, the NZLAM 2009–2010 distribution is low, while the Stuart (2011) and NZMS 1951-80 distributions are high.

Discussion

Despite the best efforts to place the new gauges in potentially high precipitation regions, the new precipitation observations are lower than those observed in the Cropp River catchment in the Hokitika region and the Poseidon Creek catchment in the Milford region (Henderson and Thompson, 1999). One of the indications for anticipating extreme mean annual precipitation in the study region was that New Zealand's record-high rainfall totals for durations from 3 hours to 72 hours was set at the Alex Knob gauge (gauge 26) in March 1982. The long-term record from this site (using a combination of gauge 26 and the later gauge 27), indicates the high totals for the March 1982 event, relative to other sites, are not typical. The record-high rainfall occurred during a moist but weak northwest flow over the region, which would be conducive to atmospheric flow blocking (McCauley and Sturman, 1999) and precipitation occurring further upwind (to the west) than what would occur during the more common stronger air flow. The variation of precipitation distributions under different synoptic situations has been identified as a limitation of mean annual precipitation distributions. A valuable extension of this work would be to prepare precipitation distributions for different weather situations, as has been done for the Lake Pukaki catchment to the east (Kerr, 2009). Precipitation magnitude in the Southern Alps has been related to the height of the topography of the related orographic barrier (Griffiths and McSaveney, 1983a; Henderson and Thompson, 1999). The distribution presented here is not consistent with such a relationship as the orographic barrier here is the highest in the country, yet the observed precipitation is not.

The mean annual precipitation estimates for the eastern edge of this region are lower than the observations from the western edge of the adjacent Lake Pukaki catchment (Kerr *et al.*, 2011). Possible explanations for this discrepancy are that the various observations are grossly in error or that there is a discontinuity in the precipitation distribution. In both regions the measurements are supported by more than one site indicating the effect is real and not a result of incorrect operation. The possibility of a discontinuity at an orographic divide has been demonstrated in precipitation modelling under the correct temperature and wind combinations (Zängl, 2008) and is analogous to snowdrift build up in the lee of a ridge (Greene *et al.*, 1999). This effect is a result of the wind flow fields in complex terrain providing preferential precipitation fallout locations where hydrometeor trajectories are directed strongly downward. Where ridgelines lie across the wind, their lee sides either provide sheltered regions for hydrometeors to fall into and through, or under conditions of lee waves, provide strongly downward-directed wind flow. Under both of these situations, regions lee of ridges will provide preferential precipitation locations that are a step change from the areas immediately to windward. This provides a reasonable explanation for the disparity between the Westland Tai Poutini National Park eastern precipitation observations and the western Lake Pukaki catchment precipitation observations. It also provides an explanation for the extreme precipitation observed in Poseidon Creek in the Milford region, and the Cropp River observations in the Hokitika region.

There is a good possibility that this lee enhancement effect is further increased through wind drift of snow from the extensive snow fields of the Fox and Franz Josef glacier neves. Where snow falls in the neves under low wind conditions, subsequent high winds are often observed to redistribute the snow (Purdie *et al.*, 2011b) which will end up being blown over the leeward ridge line into the western edge of the Lake Pukaki catchment. While this occurs subsequent to the precipitation event, precipitation gauges are unable to distinguish between the processes. The magnitude of this effect is currently unknown.

The ideal sampling density of precipitation gauges depends on the spatial variability of precipitation, yet knowledge of the spatial variability is limited by the sampling density. Generally, gauge density is financially constrained, particularly in complex terrain where access and communication can be problematic. In lieu of high resolution observations, relating precipitation variability to topographic variability is not unreasonable and may be included in the interpolation technique (Kyriakidis *et al.*, 2001).

Topography affects both where the precipitation is created in the atmosphere, and where it lands on the ground through influencing the fall trajectory of hydrometeors. Large-scale air masses approaching raised topography during stable atmospheric conditions commonly flow over a lower layer of stable, valley-filling buffered air with a turbulent shear layer between (Rotunno and Houze, 2007). Hydrometeor creation and growth occurs where the air mass ascent occurs windward of the mountain terrain (Smith *et al.*, 2003) and within the turbulent shear layer. The lower layer of stable, valley-filling buffer is effectively a cushion of air encapsulating the major features of the topography, so that much of the precipitation creation processes are blind to the fine-scale topographic features. This provides a physical explanation for why reducing the horizontal resolution of terrain in weather models below 4-10 km has little effect on modelled precipitation magnitudes (e.g., Sharples *et al.*, 2005; Webster *et al.*, 2008). Below the scale at which the orographic boundary layer is resolved, there is little improvement in the modelling of the precipitation formation mechanisms, whereas the modelling of where the hydrometeors end up is still strongly scale dependent (Blocken *et al.*, 2005) as the near-surface terrain-to-wind interactions are increasingly resolved. Inclusion of hydrometeor trajectories in precipitation models has proven crucial for improving estimates of mountain precipitation distribution (Sinclair *et al.*, 1997). For low density gauge networks, determining whether a precipitation gauge is representing a broadscale precipitation field or a fine-scale precipitation anomaly is impossible. Interpolation of gauge measurements as in this study prevents identifying spatial fields smaller than the gauge density, and assumes the gauges are representative of the precipitation spatial fields surrounding them. This assumption becomes less valid as the terrain becomes increasingly complex. An approach to understanding the higher-resolution variability of precipitation distribution is through application of these terrain-precipitation interactions in high resolution precipitation modelling. This is currently done at large spatial scales (degrees) for global re-analysis products, e.g., from ECMWF (Uppala *et al.*, 2005) or NCEP-NCAR (Kalnay *et al.*, 1996) with mountain sub-catchment scale at the forefront of reanalysis efforts, e.g., the EURO4m-APGD 5 km resolution precipitation reanalysis for the European Alps (Isotta *et al.*, 2014).

Unfortunately, validation of such models is still largely reliant on the gauge density. Solutions to observing highly variable precipitation fields other than increased gauge density include rain radar (e.g., Purdy *et al.*, 2005) and satellite remote sensing products (e.g., Liu *et al.*, 2016). Application of these observation methods to clarify New Zealand terrain-precipitation relationships is an opportunity for future research.

Precipitation gauge undercatch is an important consideration in this very high precipitation region in that even 5% undercatch can amount to half a metre of precipitation. Where snow fall occurs or elevated gauges are used the undercatch is likely to be even more significant. The gauges installed for this project had Alter-style wind shields to limit undercatch, and temperature and windspeed variables were measured to enable undercatch correction to be carried out in post processing. While high undercatch values were anticipated, the low windspeeds observed, and the vast majority of precipitation occurring in warm conditions, led to undercatch estimates of 7% or less. In the lower sites, the addition of the Alter shield to the 2 m high gauges limited the undercatch to values normally observed in unshielded rain gauges with lower orifice heights. Having said that, inclusion of undercatch makes a considerable difference to the resulting magnitude of the precipitation distribution. Efforts to balance water budgets in the Rakaia (McSaveney, 1985) and Hokitika (Duncan, 1992) catchments have failed, with the unaccounted-for undercatch likely to be a considerable part of the imbalance. Similarly, an undercatch of 10% was required to balance the water budget for the Cropp catchment (Griffiths and McSaveney, 1983b). By minimising undercatch with the wind shields, and correcting using empirically-derived formulae that account for windspeed and hydrometeor phase, undercatch may be eliminated as a cause of water budget imbalance. By including undercatch here, the precipitation distribution provided is ready for hydrological application.

Conclusion

All available precipitation observations in the Westland Tai Poutini National Park were combined with observations from nine new precipitation gauges to provide an undercatch-corrected mean annual 1981–2010 precipitation distribution for the region. The distribution indicates mean annual precipitation increases from 3500 mm at the coast to more than 10000 mm near the centre of the region. No consistent cross-mountain precipitation profile was able to be determined from the observations with variations attributed to the different ridge and valley orientations that influence where precipitation lands. The average annual 1981–2010 precipitation for the whole region was 6200 mm. Undercatch estimates based on empirical calculations considering wind speed, shielding and hydrometeor species ranged from 4% to 7% for the 2 m high Alter shielded gauges that were installed in sub-alpine regions. The estimated undercatch reflects the high proportion of liquid precipitation and the low wind speeds observed during precipitation events. The new distribution indicates the NZMS 1951–1980 precipitation distribution (NZMS, 1985a) overestimates precipitation, especially in the eastern areas of the region.

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