High resolution precipitation fields for the Clutha catchment

A. M. Jobst[1], D. G. Kingston[1] and N. J. Cullen[1]

[1] *Department of Geography, University of Otago, PO Box 56, Dunedin, New Zealand*

Correspondence: andijobst@gmail.com

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Abstract

NIWA's Virtual Climate Station Network (VCSN) is currently the only product that offers interpolated daily precipitation data for the whole of New Zealand. The VCSN has been used to successfully model hydrological processes in several catchments but it still contains significant biases for high elevation catchments. In this study, an attempt was made to create improved daily precipitation fields for New Zealand's largest catchment, the Clutha River. The grids have a higher spatial resolution than the VCSN (1 km^2 vs. ~5 km^2) and were created using a trivariate thin plate spline based on a modified version of the 30-year rainfall normal surface that was used as part of the VCSN approach. The original rainfall surface was adjusted because a water balance validation with the hydrological model WaSiM revealed substantial biases in several sub-catchments of the upper Clutha (from -13% to +72%). After the correction, the 20-year water balance error (1992-2012) did not exceed ±5% at any of the streamflow gauges used. Compared to the fields generated here, the annual precipitation of the VCSN is generally lower with the largest differences in the headwaters (> -2000 mm). Consequently, when compared to the VCSN the mean annual precipitation averaged across the Clutha catchment was found to be higher in this study (1415 mm vs. 1258 mm).

1. Introduction

The spatial distribution of precipitation across the South Island of New Zealand is characterised by large variability. While correct representation of daily precipitation is key for hydrological modelling studies (Tait et al., 2012), sparse station networks can hamper the generation of realistic spatial estimates. In addition to the common problem of insufficient data availability in alpine catchments (Suprit and Shankar, 2008; Schönbrodt-Stitt et al., 2013), wind-driven undercatch and evaporation can cause systematic measurement errors (Mekis and Hogg, 1999). Such errors can then negatively affect the performance of hydrological models (Oudin et al., 2006).

In the Southern Alps the highest annual totals tend to occur approximately 20 km upwind of the main divide (Wratt et al., 2000), which is a direct result of the interaction of a predominantly westerly airflow and the orography. Besides very high amounts of orographic precipitation to the west of the main divide, strong transmountain winds can cause large amounts of precipitation to fall on

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the leeward side and this so-called spillover can extend up to 20 km eastwards from the main divide (Sinclair et al., 1997). With spillover being the dominant source of precipitation for the headwater catchments to the east of the main divide, the correlation between precipitation and elevation for the Southern Alps is rather weak by global standards (Wratt et al., 2000; Tait et al., 2006).

To provide input for hydrological models and other environmental applications Tait et al. (2006) estimated daily rainfall on a 0.05° grid (VCSN) for the whole of New Zealand using a trivariate thin-plate spline (TS). The TS was found to perform best if a rainfall normal surface was used as an independent covariable instead of elevation, which highlights the alternative role of the Southern Alps when compared to other alpine regions in terms of precipitation – elevation relationships (Lauscher, 1976; Marke, 2011). While the VCSN fields constitute a valuable data set for modelling studies in New Zealand, the use of independent regional council data highlighted that the daily fields still have significant errors in some regions of the Southern Alps with monthly mean absolute errors between 30 and 100 mm (Tait et al., 2012).

This study focuses on the Clutha catchment, which is New Zealand's largest catchment by area and mean flow. The Clutha's natural water resources are used extensively for hydropower generation and irrigation schemes. As part of a wider hydrological modelling study (Jobst et al., 2018) an attempt was made to improve on the VCSN and provide a more realistic precipitation input for a fully distributed hydrological model. A similar approach as described in Tait et al. (2006) was adopted to generate daily grids at the required spatial resolution of 1 km^2 between 1990 and 2012. The main differences between the VCSN approach and this study are the higher spatial resolution, a small number of additional precipitation records (i.e. regional council data) and a modified version of the 30-year (1951-1980) rainfall normal surface (as described in Tait et al. (2006)) that is used as part of the TS interpolation. Biases were assessed using a water balance approach in combination with the fully distributed hydrological model WaSiM (Schulla, 2012).

2. Methods

2.1 Data sources

A total of 76 sites with variable record lengths were included for the interpolation of daily precipitation (Figure 1). The majority of the sites are operated by NIWA (73) and three additional records were provided by the Otago Regional Council (ORC). Compared to the low number of sites recording temperature in the domain (Jobst et al., 2017), the precipitation network is more extensive and covers most parts of the Clutha catchment. However, most of these sites are located in intermontane valleys and the upper headwaters that originate downwind from the main divide (~0-12 km) can be considered ungauged, with the only exception being the relatively short record (~4 years) at Young River (P-O1). In Figure 2 the mean annual precipitation totals of all 76 records are plotted against the corresponding distances to the main divide. The highest totals were recorded at the two Milford Sound sites (P-N3 and P-N4), while the shorter P-O1 record has the highest annual precipitation (> 5000 mm) of any site inside the watershed. Further inland and towards the east coast, precipitation totals decrease rapidly and remain below 1000 mm at most sites.

2.2 Extension of the Young River precipitation record

The rainfall station at P-O1 (operated by ORC) is located approximately 4 km to the lee of the main divide. The record is especially important as it is the only station within close proximity of the main divide, a zone where the intensity of spillover is expected to be strongest. To maximize the usage of the site's relatively short record (1/9/2008 – 1/9/2013) linear regression was used to extend the record through the remaining time period

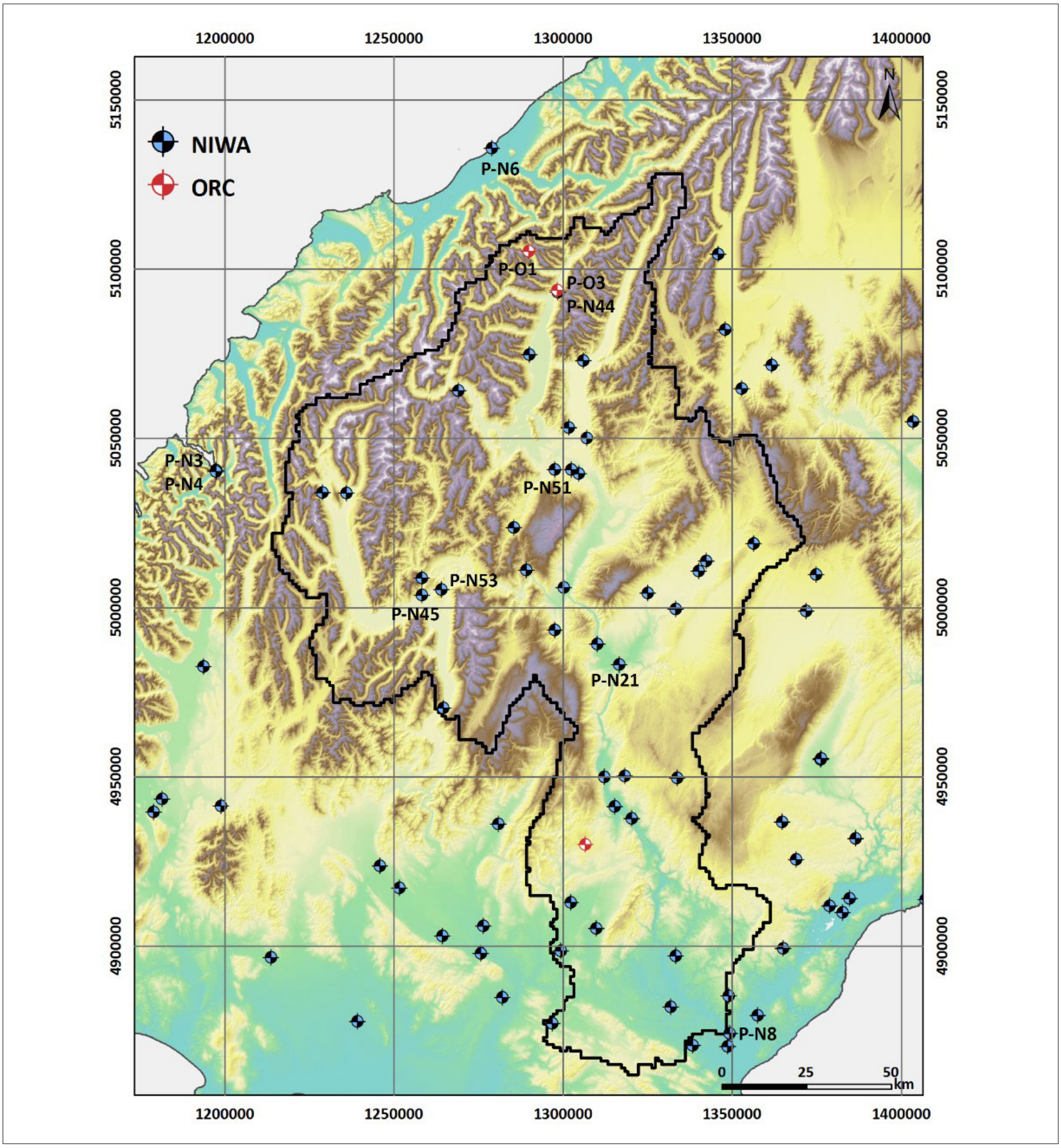

Figure 1: NIWA and ORC precipitation sites used for the daily interpolation. Mean annual precipitation of the labelled sites is shown in Figure 2 (note that site P-N44 is occluded by P-O3). The black line shows the Clutha catchment with the gauge in Balclutha as the outlet.

(1/4/1992 – 31/8/2008). The first regression (Equation 1) is based on the ORC site P-O3 at Makarora (15 km SE), which is the same rainfall station used by Cullen and Conway (2015) to reconstruct precipitation at Brewster Glacier. Importantly, P-O3 has the same tipping bucket instrument as the P-O1 site. Given that the record of P-O3 only dates back to 5/11/1997, the record of a manual daily rain gauge (P-N44), which is operated by

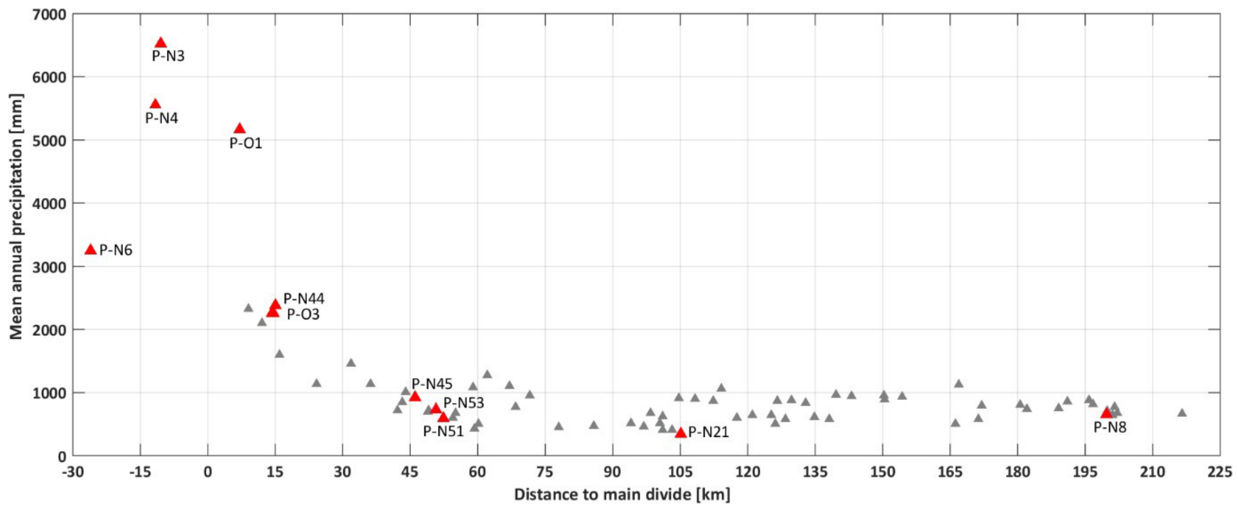

Figure 2: Mean annual precipitation (regular year) of all sites between 1992 and 2011 (shorter records are also plotted, e.g. P-O3 1998-2011) against distance to main divide. The location of the labelled sites (red triangles) is also shown in Figure 1.

NIWA and located approximately 500m from site P-O3, was used for the second regression (Equation 2), covering the remaining time period.

$$P\text{-}O1_{extended1} = 2.0308 * MAKARORA_{ORC} + 1.3282 \qquad (1)$$

$$P\text{-}O1_{extended2} = 1.5643 * MAKARORA_{NIWA} + 4.0276 \qquad (2)$$

Further, any scaled values were set to 0 mm if no precipitation was recorded for that time step. The calibration and validation periods were defined from 1/9/2008 to 31/8/2011 and from 1/9/2011 to 1/9/2013, respectively. The performance of the two best-fit regression models can be seen in Table 1 and Figure 3, where the first regression model (Equation 1) was found to have a better fit during both the calibration and validation period.

2.3 Undercatch correction step

Before the interpolation was carried out, a wind-dependent undercatch correction was performed. The empirical approach of Yang et al. (1998), which has been used by Kerr et al. (2011) in the Lake Pukaki catchment requires mean temperature and wind speed at the gauge height as input, and differentiates between solid, mixed and liquid precipitation. As most of the precipitation sites in the Clutha domain do not record wind speed or air temperature, daily fields of these two variables were instead used. A total of 22 stations were used for the interpolation of air temperature and 26 sites for wind speed (with only 13 stations located inside the catchment and only 7 stations covering the entire data period). The daily temperature grids were presented in Jobst et al. (2017) and are based on a TS and a monthly lapse rate

Table 1: Validation of the two regression models P-O1$_{extended1}$ and P-O1$_{extended2}$. Performance criteria (R2 and RMSE) were calculated for the calibration (CAL) and validation (VAL) period, respectively.

Scaled site	R^2 (CAL)	R^2(VAL)	RMSE(CAL)	RMSE(VAL)	Extension period
P-O1$_{extended1}$	0.90	0.85	10.10	12.05	05/11/1997-31/08/2008
P-O1$_{extended2}$	0.59	0.60	20.20	19.43	01/04/1992-04/11/1997

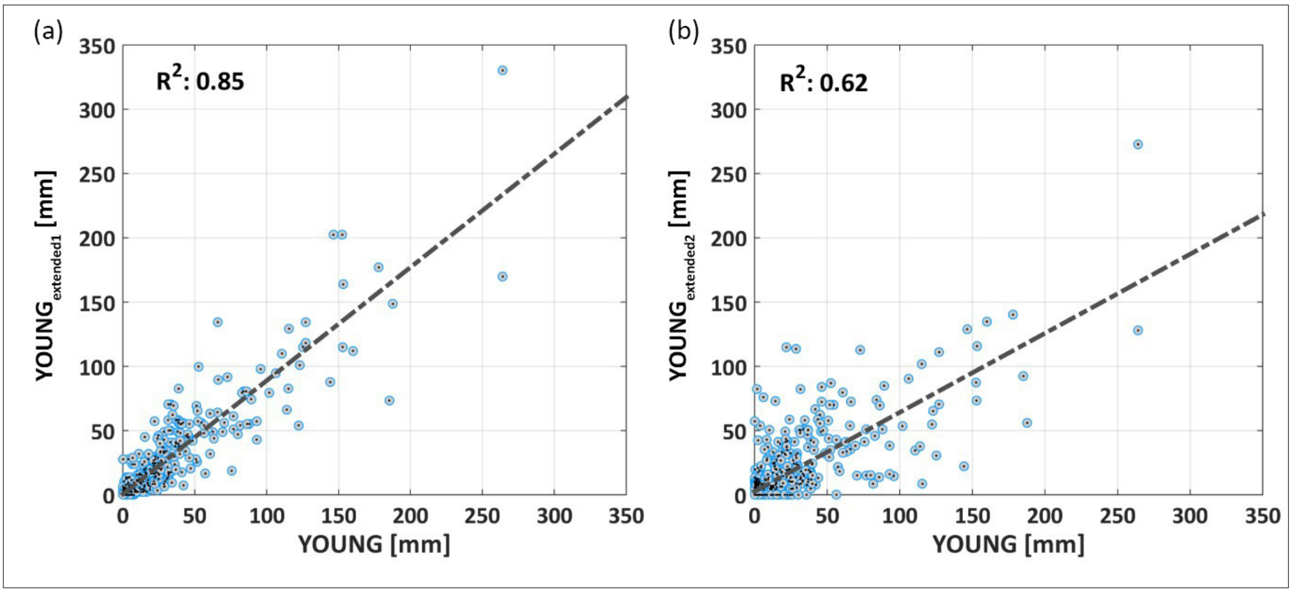

Figure 3: Scatterplots showing daily precipitation between YOUNG (= Site P-O1) and $YOUNG_{extended}$ during the validation period (1/9/2011 to 1/9/2013) for (a) the P-O1 $_{extended1}$ and (b) the P-O1 $_{extended2}$ regression model. The dashed line represents the line of best-fit.

model. The wind fields were generated using an elevation based TS run on a relatively sparse network of wind gauges.

2.4 Validation using water balance approach

After the undercatch correction, the 30-year rainfall normal surface was iteratively adjusted using a water balance approach and the assumption that natural stores of water are equal to zero over longer time periods. The fully distributed hydrological model WaSiM was used as a tool to approximate the true mean annual precipitation of the Clutha basin on a sub-catchment scale. The WaSiM model (described in Jobst et al. (2018)) models potential evapotranspiration via the Penman-Monteith approach, which is limited by soil water content and capillary pressure resulting in actual evapotranspiration (AET). Changes in the snow, unsaturated soil and groundwater stores are unlikely to have a significant effect on the water balance over the 20-year period. The same holds for the relatively small volume of glaciers located in the headwaters of the Clutha covering only ~0.7% (i.e. ~147 km^2) of the catchment (Chinn, 2001). This restricts the uncertainty introduced by WaSiM to the term of AET, which was computed at 518 mm. This number agrees well with the 540 mm estimate that Sirguey (2009) used for the upper Waitaki catchment and which is based on the averages of three Southern Alps studies (Anderton, 1974; Fitzharris and Garr, 1995; McKerchar and Pearson, 1997). Consequently, the error between observed and modelled streamflow was then assigned to over or under estimations of annual precipitation totals in the corresponding sub-catchments. The water balance validation was carried out over a 20-year period (1/4/1992-31/3/2012) for eight streamflow gauges, with the threshold for error (stopping criterion) defined as not being allowed to exceed ±5% at any of the sites.

A pragmatic approach was used to adjust the original rainfall normal surface ($SURF_{org}$) using a sub-catchment based correction factor grid. Biases in $SURF_{org}$ were assumed to be greater close to the main divide due to a lack of rain gauges and the steep gradient in spillover precipitation leeward from the main divide. From the main divide to the end of the spillover zone correction factors were thus reduced or increased linearly to one.

The spillover zone was defined between 0 and 24 km from the main divide based on the findings of Chater and Sturman (1998). Their study focused on the Waimakariri catchment, which is located at a relatively large distance (~200 km) to the northeast of the Clutha but has a comparable elevation range and is therefore assumed to have similar orographic uplift. Further linear factors were assigned to sub-catchments further inland. In order to create smooth transitions between neighbouring sub-catchments correction factors were assigned to the cells of the stream network, which were interpolated resulting in a continuous correction grid. The grid was then multiplied with $SURF_{org}$ to produce the adjusted rainfall surface ($SURF_{mod}$) and the TS was then rerun with $SURF_{mod}$ as the covariate.

3. Results

3.1 The water balance validation

The water balance validation of TS_{org} (TS using the $SURF_{org}$ shown in Figure 4) revealed substantial over- and underestimations of streamflow (and consequently precipitation) in several sub-catchments (Figure 5). The largest positive bias (72%) was calculated for the Shotover River at Peat's Hut (Shotover at Bowens Peak: 61%). As shown by Figure 4, $SURF_{org}$ reaches high totals exceeding 4000 mm in the upper ranges of the Shotover (indicated by white arrow). This local maximum shows substantially higher totals than other parts of the upper Clutha that are at a similar distance to the main divide. The spatial pattern of $SURF_{org}$ clearly follows the terrain of the upper Shotover, which has a plateau-like shape and on average reaches higher elevations than the neighbouring sub-catchments. During the expert guided process underlying the generation of $SURF_{org}$, a strong orographic effect must have been expected to enhance precipitation in the ungauged ridges of the upper Shotover (Tait et al., 2006). However, the large positive bias in Figure 5 appears to contradict this assumption.

For the Kawarau catchment opposing biases were found for the gauges at Frankton (9%) and The Hillocks (-5%). The positive bias at Frankton (Lake Wakatipu outlet) points to a substantial overestimation of precipitation in the remaining Wakatipu tributaries south of the Hillocks. The streamflow error was also found to be positive for Lake Wanaka (5%) and Lake Hawea (20%). Further inland, a relatively large positive bias (18%) was found for the intermontane Nevis valley, while the bias in the

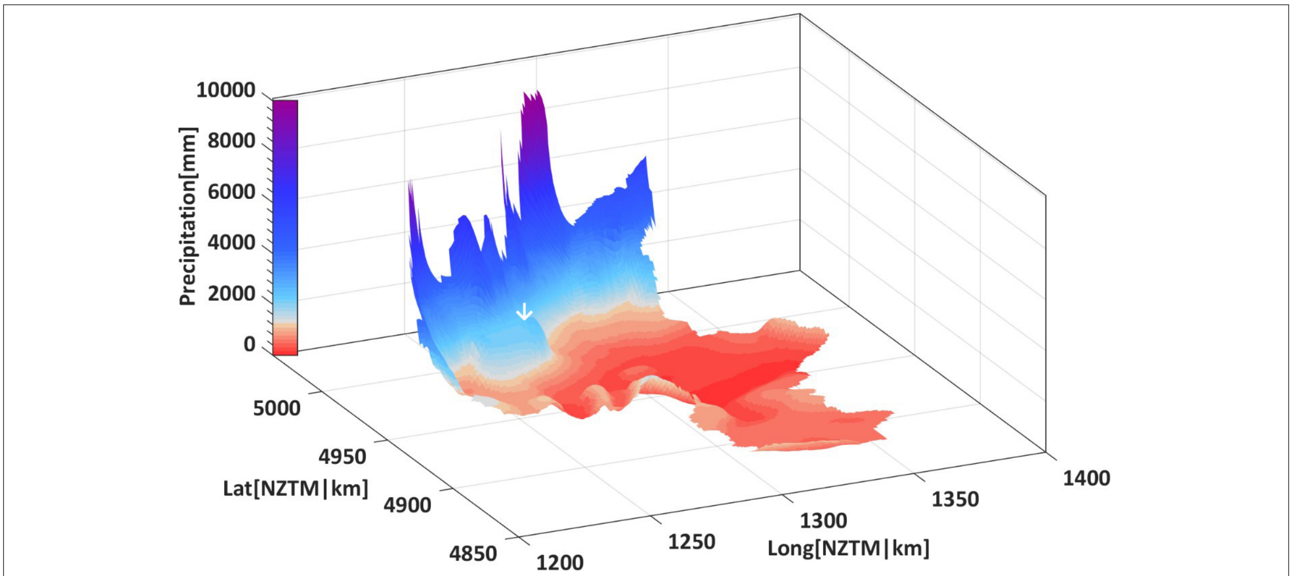

Figure 4: The original rainfall normal surface ($SURF_{org}$) clipped by the Clutha watershed (arrow points to the upper Shotover sub-catchment).

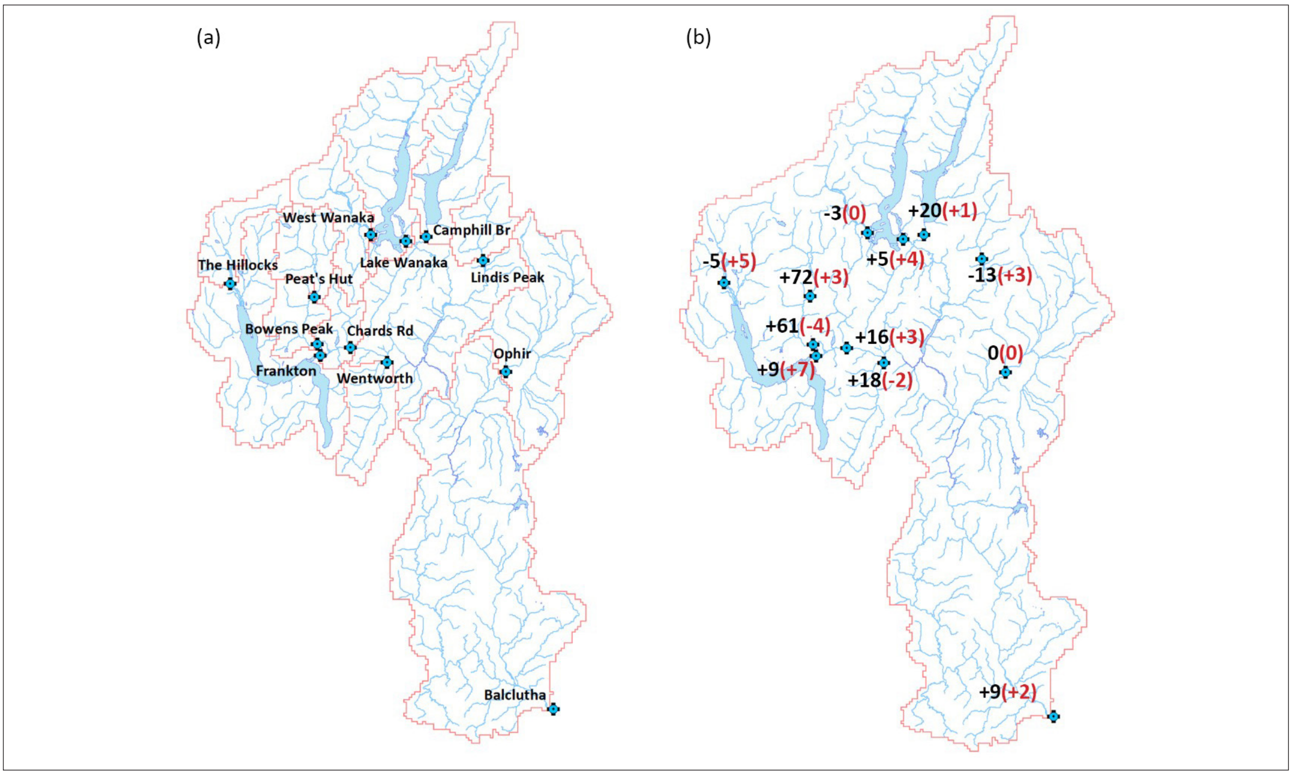

Figure 5: (a) The network of flow gauges and their corresponding sub-catchments (sub-catchments were derived using the topography based tool TANALYS (Schulla, 2012)). (b) The errors (%) between modelled and observed mean annual streamflow (1/4/1992 – 31/3/2012) for the TS_{org} forced run (black) and the TS_{mod} forced run (red).

upper Lindis (Lindis Peak) was negative (-13%). At the catchment's outlet (i.e. Balclutha) the combined upstream errors resulted in a substantial positive bias of 9%.

The final correction factor grid that was used to adapt $SURF_{org}$ (Figure 6a) has values ranging from 0.45 (Shotover) to 1.15 (The Hillocks). Correction factors tend steeply towards 1 when adjoining an area of the catchment that did not require correction. The factor grid was then multiplied with $SURF_{org}$ resulting in $SURF_{mod}$, with the difference between the two surfaces unfolded by Figure 6b.

As shown in Figure 5b (red font) the use of $SURF_{mod}$ as a covariate in the TS interpolation (TS_{mod}) led to a much more realistic simulation of streamflow. The most obvious difference between the two surfaces is the reduction of precipitation in the upper Shotover (Figure 6b), where the leeward extension of the high precipitation zone from the main divide has been substantially reduced, eliminating the previously large overestimation of observed streamflow. For all of the remaining sub-catchments with 20-year records the biases also remained within ±5%.

3.2 The annual catchment precipitation

Based on the daily fields created in this study, most of the Clutha catchment has annual precipitation of less than 1000 mm with the driest areas in the centre receiving less than 500 mm per year (Figure 7). At an approximate distance of 40 km from the main divide, annual totals exceed the catchment average (1415 mm; see dashed contour line) and increase rapidly until reaching 4000 mm between 2 and 10 km from the main divide. The highest precipitation totals ranging from 4000 mm to 10000 mm (exceeding 10000 mm in isolated cells) are

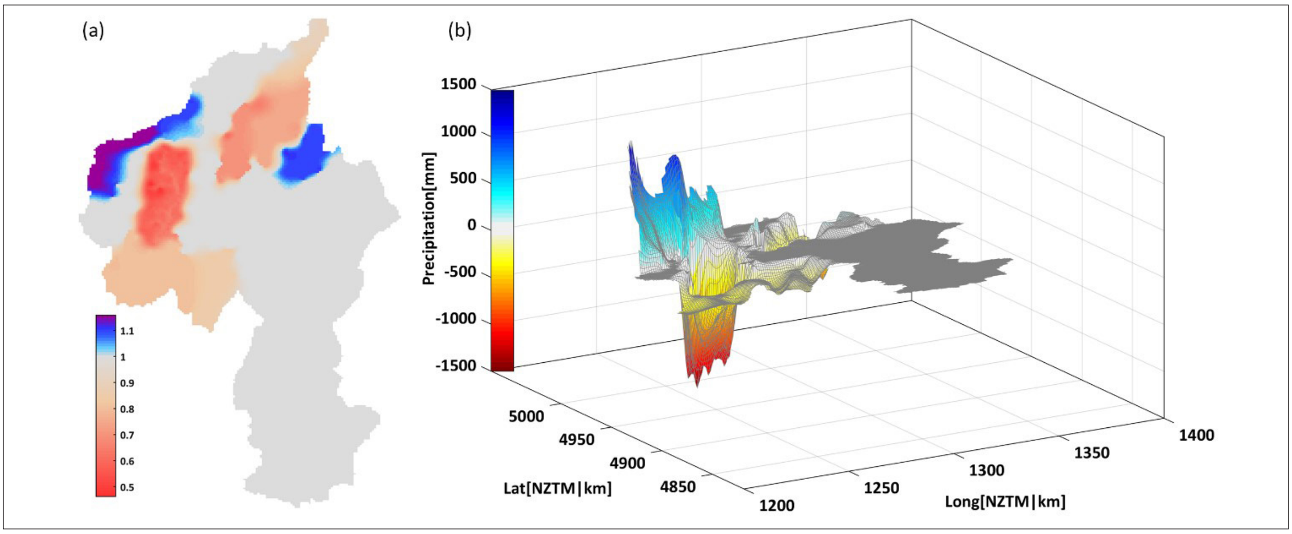

Figure 6: (a) The correction factor grid that was used to generate $SURF_{mod}$. (b) Difference between $SURF_{mod}$ and $SURF_{org}$.

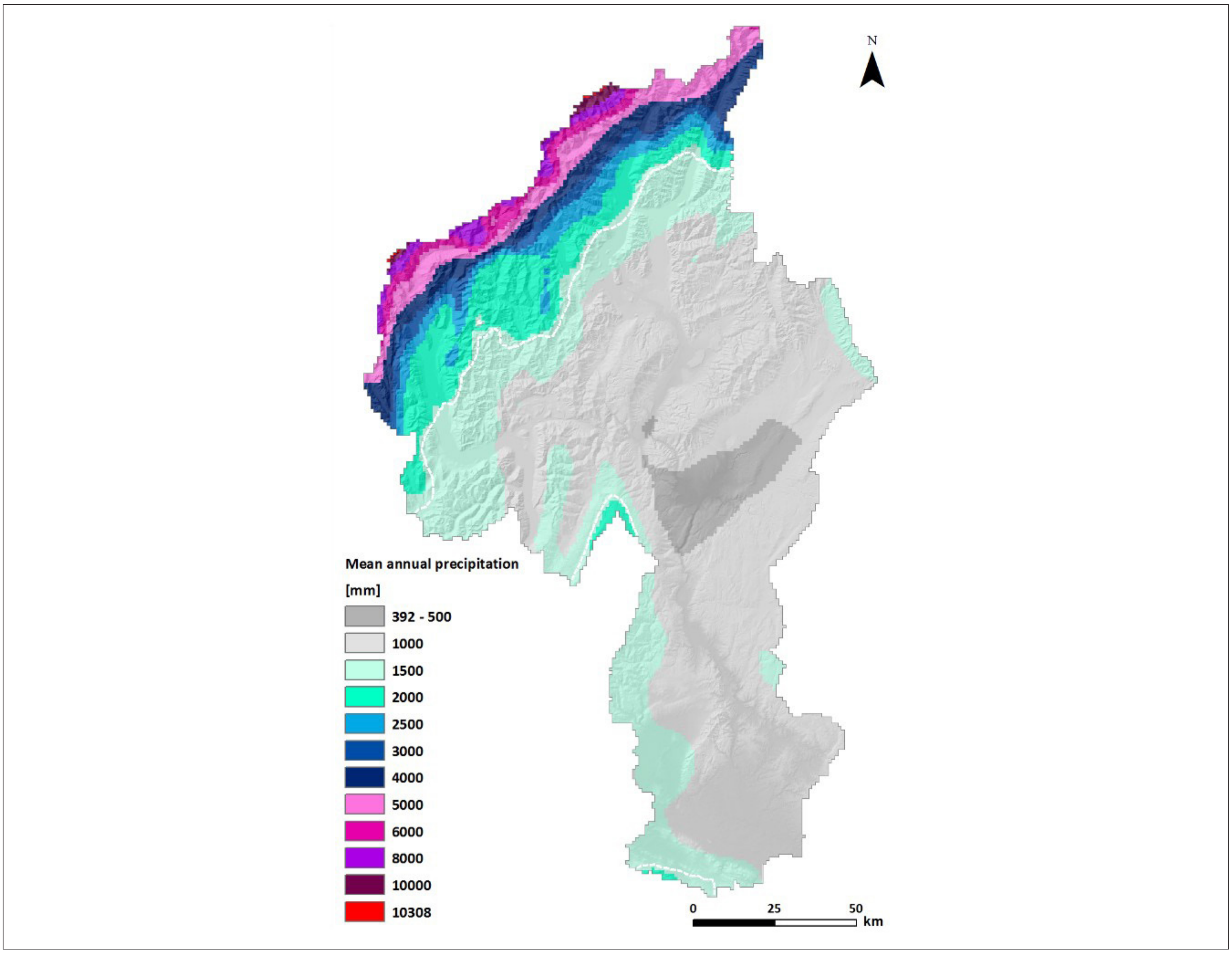

Figure 7: Mean annual (hydrological years) precipitation classes (mm) in the Clutha watershed based on the daily TS_{mod} fields. The dashed white line represents the 1415 mm isohyet, which corresponds to the mean precipitation of the catchment during that period.

Table 2: Mean annual precipitation in the Clutha catchment for hydrological years (1/4/1992 – 31/3/2012) based on VCSN and different versions of TS_{mod}: $SURF_{org}$ without ORC data and without undercatch correction, $SURF_{org}$ without ORC data and with undercatch correction, $SURF_{org}$ with ORC data and with undercatch correction, $SURF_{mod}$ with ORC data and with undercatch correction (= the complete approach).

Interpolation approach	Mean annual precipitation [mm]	Difference relative to VCSN [%]
VCSN (bilinear interpolation from ~5km to 1km)	1258	-
$SURF_{org}$_noORC_noUC	1370	8.9
$SURF_{org}$_noORC_UC	1428	13.5
$SURF_{org}$_ORC_UC	1484	18
$SURF_{mod}$_ORC_UC (=TS_{mod})	1415	12.5

found within that remaining zone. Finally, the annual water balance of the catchment is comprised of 1415 mm precipitation, of which 518 mm correspond to AET and 896 mm to streamflow (change in natural stores: 1 mm).

The effects of the various changes made with respect to the VCSN approach are shown in Figure 8 (see Table 2 for the mean catchment precipitation). When using $SURF_{org}$ in combination with the NIWA sites only and without undercatch correction annual precipitation is higher in most parts of the catchment (except in the north-eastern part) (Figure 8a). Adding the undercatch correction (Figure 8b) results in a moderate increase of precipitation (i.e. 4.2% overall change) with a similar pattern (compared to Figure 8a) of positive and negative differences across the catchment. Including the ORC sites substantially increases precipitation in the upper headwaters causing a predominantly positive difference that also extends into the north-western part of the catchment (Figure 8c). The effect of incorporating $SURF_{mod}$ (final component) is most apparent for the Shotover and Hawea sub-catchments (reduced precipitation up to 500-750 mm), and for the north-western headwaters (Figure 8d). Overall, the mean annual precipitation of the final product (i.e. TS_{mod}) is 12.5% higher compared to the VCSN (1258 mm) with positive differences exceeding 2000 mm towards the main divide.

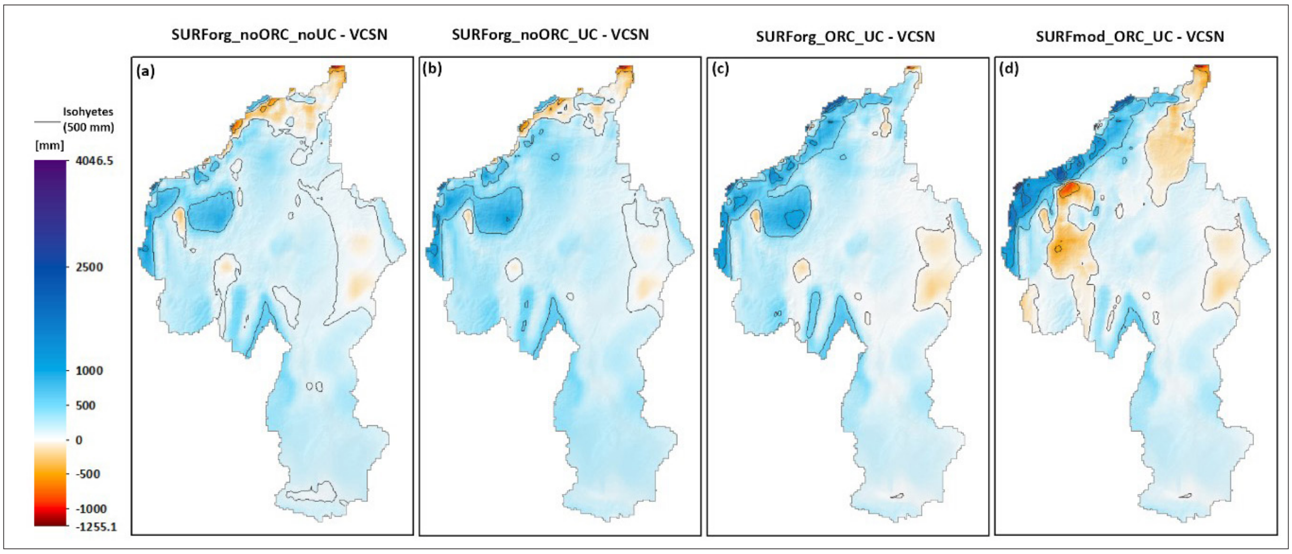

Figure 8: Differences between the mean annual precipitation of the VCSN and different versions of TS_{mod}: (a) $SURF_{org}$ without ORC data and without undercatch correction, (b) $SURF_{org}$ without ORC data and with undercatch correction, (c) $SURF_{org}$ with ORC data and with undercatch correction, (d) $SURF_{mod}$ with ORC data and with undercatch correction, i.e. the complete approach.

4. Discussion

The undercatch correction that was carried out before the interpolation of the station data was deemed necessary as undercatch is a known problem of point-based precipitation measurements that has been reported for many alpine regions (Yang et al., 1998; Mekis and Hogg, 1999). In the Pukaki basin with a comparable, albeit greater, precipitation gradient (710 – 13200 mm) the error induced by undercatch was estimated to range between 6 and 16% (Kerr et al., 2011). For the Clutha catchment as a whole the effect of undercatch correction was found to be smaller (i.e. 4.2%), but this value is expected to be higher for the upper Clutha where the terrain is more comparable to the alpine Pukaki catchment.

The technique that was used here to interpolate the undercatch corrected records follows up on existing studies that have used thin-plate spline interpolation for generating precipitation estimates in New Zealand (Tait et al., 2006; Sirguey, 2009). These studies showed that a TS with $SURF_{org}$ as a covariate resulted in the best accuracy and outperformed alternative approaches such as a bivariate spline or a trivariate spline with elevation as a covariate. In this study, $SURF_{org}$ was adjusted for some of the sub-catchments to allow for a realistic simulation of the water balance. The major modifications involved a reduction of orographic precipitation in the Shotover River, an increase of precipitation in the spillover zone of the Dart River and a decrease of precipitation in the remaining tributaries of Lake Wakatipu. Further adjustments were made by reducing precipitation in the Nevis and increasing precipitation in the upper Lindis. These modifications were considered justifiable as the construction of $SURF_{org}$ involved expert interpolation for locations where no observations were available (Tait et al., 2006). Using a water balance approach to estimate annual runoff across New Zealand, Woods et al. (2006) also found that an additional bias correction of the VCSN precipitation was necessary for several catchments to keep the model error below ±25% (including sub-catchments of the upper Clutha). In their study the error based on AET, precipitation and modelled streamflow was interpolated resulting in a smoothed bias surface which they used to correct their runoff estimates. The approach has also been adopted by Poyck et al. (2011) to model (i.e. TopNet) historical snow and streamflow processes in the Clutha catchment.

It should be noted that any potential errors associated with the term of AET would have introduced some uncertainty to the error assessment of modelled streamflow. Even though the uncertainty of modelled AET cannot be quantified, it is assumed to be relatively unimportant in the upper part of the Clutha where annual precipitation exceeds AET substantially. However, inaccuracies linked to modelled AET could be more important in the central parts of the catchment (i.e. Nevis and Lindis). Despite these uncertainties, the water balance modelling strongly suggested that the annual precipitation amounts of $SURF_{org}$ were inconsistent with the observed river flow of the affected sub-catchments between 1992 and 2012.

The differences between the two surfaces that were required to approximate the observed flow and hence the water balance suggest the following. First, precipitation in the north-western part of the Clutha is especially high, which could be explained by a particularly strong orographic uplift in this area and a resulting intensification in spillover precipitation. Second, the elevation of the terrain on the leeward side of the divide (i.e. the Shotover watershed) seems to have a substantially smaller effect on the precipitation intensity as suggested by $SURF_{org}$. The same applies (but to a lesser extent) for the Wakatipu sub-catchment where precipitation needed to be increased in the headwaters (error at The Hillocks of -5%) and decreased further eastwards (error at Frankton of +8%). The lack of rain gauges in the eastern parts of the Wakatipu basin means that $SURF_{org}$ in this area had to be based on expert knowledge, which could explain the overestimation of precipitation here. Sirguey (2009) identified similar discrepancies for the Waitaki catchment, where $SURF_{org}$ showed substantial departures from the area weighted annual precipitation (as targeted by a 12-year water balance) in the sub-catchments Lake Pukaki (26%), Lake Ohau (-11%) and Lake Tekapo (-9%). Considering the dominance of the precipitation term (an order of magnitude greater than AET) and the extreme precipitation gradients of these catchments (e.g. the Waitaki and the Clutha) the use of flow records supplemented with estimates of AET (Sirguey, 2009) or modelled AET (Tait et al., 2006; this study) can thus be regarded as a useful approach to reduce errors in the precipitation term of a catchment.

While no precipitation data was available along the main divide of the Clutha watershed, Figure 2 suggests that the precipitation maximum is located somewhere between the sites at Young River and Milford Sound, which corresponds to 7 km east and 12 km west of the main divide, respectively. Hence a reasonably dense network of rain gauges upwind and downwind of the spill over zone is essential for capturing the actual distribution of precipitation across the Southern Alps. This highlights the importance of gauges located in the heavy precipitation area (i.e. Young River), where precipitation totals decrease dramatically over short horizontal distances.

As described in Tait et al. (2006) the use of $SURF_{org}$ outperformed the use of elevation as a covariate in the TS, which was shown by conducting a water balance validation. The remaining errors in the VCSN were still large for parts of the Southern Alps and ranged from -10 to -50% for the upper Clutha. The errors shown here when using $SURF_{org}$ were substantially lower for West Wanaka (-3%) and The Hillocks (-5%). As indicated by Figure 8c, including the ORC sites (Young River/ P-O1 in particular) resulted in a substantial increase of precipitation in the headwaters of these sub-catchments which would have caused a substantial reduction of an otherwise comparable negative bias (with the VCSN). The undercatch correction would have also contributed to the bias reduction as shown in Figure 8b.

Tait et al. (2012) demonstrated that by including regional council data uncertainties in the VCSN product could be reduced (New Zealand wide: ~50% reduction of model error). However, due to data sharing difficulties between regional councils and the national climate database, the original VCSN (Tait et al., 2006) is still used as the operational product (Tait et al., 2012). Thus, based on the water balance validation conducted here the generated fields of daily precipitation constitute an improvement over the operational VCSN product as they offer a more realistic estimate on both the catchment and sub-catchment scale.

5. Conclusions

At a resolution of 1 km^2 the generated daily grids are considered to be representative estimates of the actual precipitation distribution inside the Clutha watershed. The fields allowed for a realistic simulation of the 1992-2012 water balance (model error within ±5% at all of the investigated sub-catchments) and can be considered as a valuable data source for environmental modelling studies focusing on the Clutha domain. The latter is highlighted by a recent hydrological modelling study in the Kawarau catchment where the TS_{mod} fields were successfully used to realistically model daily and monthly streamflow (Jobst et al., 2018). Future work could involve the use of a short term (≥ 1 year) flow network (not as prone to measurement errors as rain gauges) situated in the spillover zone of the catchment, which could help to further explore small scale errors in modelled precipitation inside the heavy rainfall zone. As mentioned by Tait et al. (2012), precipitation normal surfaces could also be specifically developed for certain synoptic patterns, which would allow improvements to be made in modelling precipitation distribution across the complex terrain that characterises the Clutha catchment. Finally, a pragmatic way to incorporate the findings of this study into NIWA's operational VCSN dataset could be to update the original rainfall normal surface (inside the Clutha catchment) with the annual precipitation surface presented here.

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