# Sensitivity analysis of hydrological modelling to climate forcing in a semi-arid mountainous catchment

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**Abstract** This study analyses the sensitivity of a hydrological model to different ways of interpolating climate forcing on the Elqui basin (5660 km$^2$) in the Chilean Andes. A 36-year period (1976–2011) was chosen in order to account for the hydro-climatic variability. Precipitation and using the inverse distance weighted methods were interpolated on a 5 × 5 km grid based on 12 and eight stations, respectively. Elevation effects on precipitation and temperature distribution were considered using a digital elevation model. Two precipitation datasets (with and without a mean altitudinal gradient) and three temperature datasets (using constant or monthly lapse rates based on altitudinal bands) were computed. All dataset combinations were assessed through the calibration of the GR4j model including a snow reservoir. Calibration was performed by the succession of Rosenbrock and simplex algorithms using a multi-objective function. Results show that the dataset based on a constant lapse rate of 6.5°C/km for temperature and no elevation effects for precipitation is sufficient to accurately simulate discharge and the snowmelt regime of the catchment over the last 30 years.

**Key words** hydro-climatic variability; hydrological modelling; snowmelt; altitudinal gradient; River Elqui; Chile

## INTRODUCTION

To optimize water resources management for irrigation and dam operation purposes, it is crucial to have accurate estimates of climate forcings in space and time. However, within complex topography the characteristic spatial scales of these forcings are typically poorly captured, notably when using a sparse network of measurements.

Topography can impact precipitation and snowfall patterns through the so-called orographic and shadowing effects; the former refers to the induced increase in precipitation rates with elevation due to the uplift, adiabatic cooling and resulting condensation of humid air masses on windward mountain sides, whereas the latter refers to the converse mechanism on leeward slopes. Due to orographic effects and weather patterns, there is ongoing research as to whether precipitation, in general, increases with elevation. For instance, precipitation accumulation trends can show considerable scatter with altitude depending on the region's exposure to wind and synoptic situations (Sevruk, 1997). Unreliable data in complex terrain at high altitudes have also led to estimate biases as large as 25% where snow accumulates (Groisman & Legates, 1994). Furthermore, depending upon the predominant wind direction, rain shadows can be created when more precipitation is deposited at or near the crest, and much less precipitation is deposited at lower elevations (Sinclair *et al.*, 1997).

Representing climate forcing becomes a critical step in producing an accurate input for hydrological models from scattered observation stations. On the other hand, analysis of the sensitivity of hydrological modelling to different datasets can offer an indicator to be used for this step (Ruelland *et al.*, 2008). Thus, the quality of climate forcing can be assessed indirectly via its ability to generate reasonable simulations of discharge through hydrological modelling. This is what we address in this paper by evaluating the sensitivity of a hydrological model to different ways of interpolating climate forcing in a semi-arid, mountainous catchment in the Chilean Andes.

## STUDY AREA

The Elqui basin is one of the main river systems of the Norte Chico region in Chile (Fig. 1). With an area of 5660 km$^2$ at the Algarrobal gauging station, this catchment presents a large altitudinal gradient with elevations ranging from 750 to 6200 m a.m.s.l. in the Andes Cordillera. Climate is semi-arid with mean annual precipitation of 120 mm (1976–2011), and extremely wet or dry years due to alternating El Niño (ENSO) and La Niña (LNSO) Southern Oscillation events. The hydrological functioning of the catchment is based on a snowmelt regime. Precipitation occurs principally in winter and is mainly stored as snow and ice in the high mountain areas. Viticulture is by far the main human activity in the basin. Most of the valley floors and part of the lower hill slopes are thus cultivated. Yet, owing to the high variability in precipitation, grape growers remain entirely dependent on surface water resources for irrigation. Water supply is notably provided by a storage dam, which is located in the upstream basin and has been in operation since 1937 (Fig. 1).

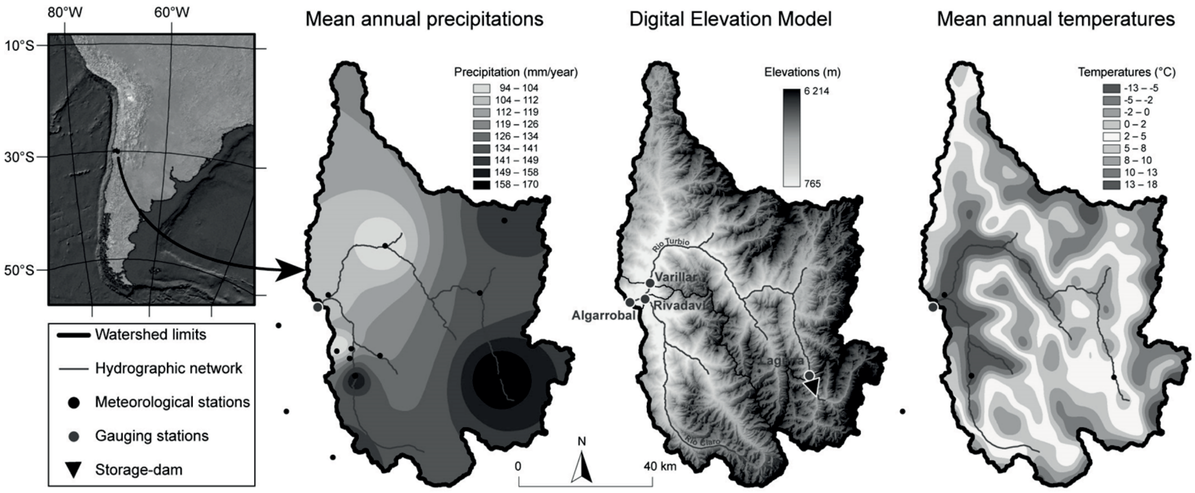


**Fig. 1** The upper Elqui catchment at Algarrobal (5600 km$^2$) in Chile: topography and mean annual precipitation and temperature over 1976–2011 according to the PWOLR-TULR dataset.

## METHODS

### Adaptation of the hydrological model GR4j to a snowmelt regime

The GR4j model (Perrin *et al*., 2003) was chosen to simulate the seasonal and interannual variations in runoff from the catchment. This daily conceptual model simulates runoff via two functions (Fig. 2). First, a production function that accounts for precipitation (net precipitation) and evapotranspiration, determines the precipitation fractions participating to runoff (effective precipitation) and supplying the production reservoir. Next, a routing function calculates runoff at the catchment outlet. The flow feeding the routing part of the model consists of effective precipitation added to percolation from the production reservoir and is divided into two fractions: (a) 90% composed of rapid runoff that is routed through a unit hydrograph (UH1) to a routing reservoir; and (b) 10% that is attributed to a more delayed runoff that is routed through a unit hydrograph (UH2). These unit hydrographs account for differences in runoff delays between the two conceptual reservoirs. GR4j originally required the calibration of four parameters.

A snow reservoir developed by Ruelland *et al.* (2011) has been included to account for the snow regime of the catchment (Fig. 2). Below a temperature threshold *x6*, a fraction *x7* of precipitation is considered as snowfall; this fraction feeds the snow reservoir that generates no flows as long as the daily temperature is below *x6*. Above the threshold *x6*, a fraction *x8*, weighted by the difference between the daily temperature and the threshold *x6*, is taken from the snow reservoir to constitute snowmelt runoff. Each day, this runoff is added to the rainfall part of precipitation in order to feed the production reservoir. Potential evapotranspiration (PE) is controlled by a coefficient *x5* (equivalent to a crop coefficient *Kc*) in order to reproduce the semi-arid context of the catchment. With this version, eight parameters must be calibrated to account for three types of runoff: snowmelt, rapid and delayed runoff.

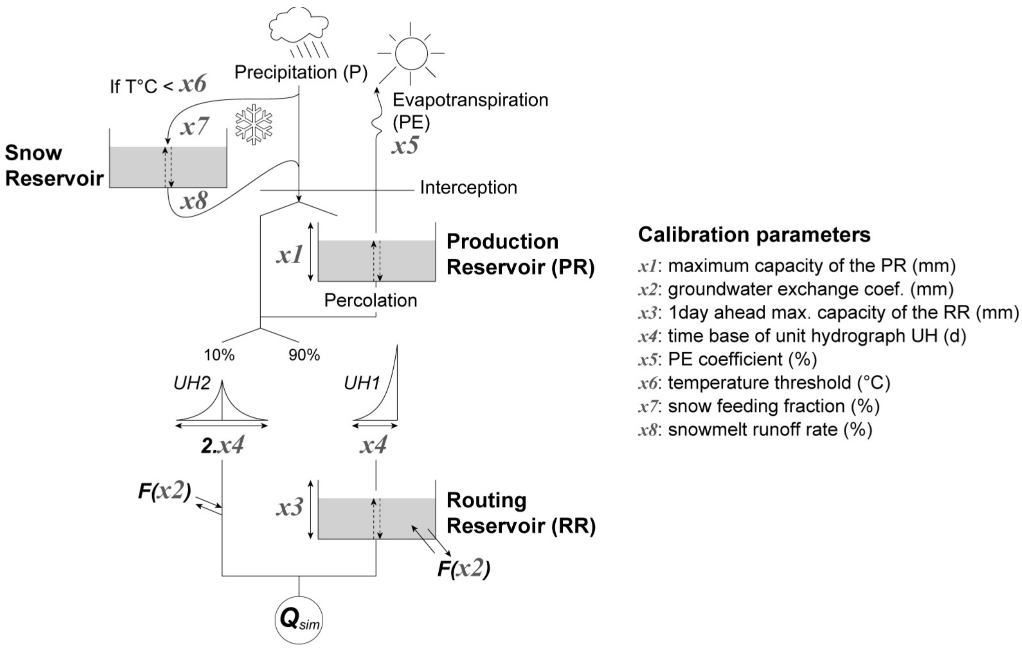


**Fig. 2** Adaptation of the GR4j model (Perrin *et al.*, 2003) to a snowmelt regime by including a snow module developed by Ruelland *et al.* (2011).

## Hydro-climatic data

In order to represent the hydro-climatic variability over the catchment, a 36-year period (1976–2011) was chosen according to data availability. Precipitation and temperature data were interpolated based on 12 and 8 stations, respectively (Fig. 1), using the inverse distance weighted method on a 5 × 5 km grid. Since no measurements were available outside the river valleys, elevation effects on precipitation and temperature distribution were considered using the SRTM digital elevation model (Fig. 1) and constant or monthly lapse rates. Two precipitation datasets were considered: precipitation with no elevation effects (PWOLR) and with a monthly mean lapse rate computed from the available precipitation stations (PWILR, Fig. 3(a)). Three temperature datasets were generated according to: (a) a constant, universal lapse rate of –6.5°C/km (TULR); (b) an average constant lapse rate by altitudinal bands (TCLR, Fig. 3(b)); and (c) a monthly mean lapse rate by altitudinal bands (TMLR, Fig. 3(b)) computed from observations. Since the only data available for calculating PE were temperature data, a formula relying on solar radiation and temperature was selected (Oudin *et al.*, 2005). Lastly, three discharge gauging stations (Laguna, Varillar and Rivadavia) corresponding to the sub-catchments of the upper Elqui River were selected on the basis of the number and quality of the time series available (Fig. 1).

## Automatic model calibration

Model calibration was based on a multi-objective function that aggregates a variety of goodness-of-fit criteria (see Ruelland *et al.*, 2012 for more details on this function):

$$F_{agg} = (1 - NSE) + |VE| + VE_{avg} \tag{1}$$

where NSE is the Nash-Sutcliffe efficiency criterion, VE the cumulative volume error, and $VE_{avg}$ the annual average relative volume error.

Calibration was performed in an 8D parameter space by searching for the minimum value of $F_{agg}$. To achieve this high-dimensional optimization efficiently, we developed an automatic calibration algorithm combining local and global optimization approaches. The goal was to handle the presence of multi-local optima appearing on the response surface and to avoid well-documented convergence problems. The algorithm consisted of repeating the following procedure

100 times: (a) 1600 random parameter sets are tested with the model; and (b) among those 1600 runs, the best solution is retained and serves as starting point for two rotating directions algorithms (Rosenbrock, 1960), the first one based on the parameters controlling the hydrological production (*x1*, *x3*, *x5*, *x7* and *x8*), the second one on all eight parameters. From the best of these 100 results, a simplex algorithm (Nelder-Mead, 1965) is finally applied to refine the numerical solution.

Calibration was performed over 1981–2011, and a 5-year warm-up period (1976–1980) was used to eliminate the influence of initial conditions in the model reservoirs.

Three catchment portions were considered for simulations (Fig. 1): (a) the Claro catchment at Rivadavia (1512 km$^2$); (b) the Turbio catchment from the Laguna dam to Varillar (3 521 km$^2$), using natural flows unaffected by the dam; and (c) the sum of the discharge from these two sub-catchments. The model was then calibrated on these three catchment portions for each of the six climate datasets, which led to a total of 18 sets of parameters.

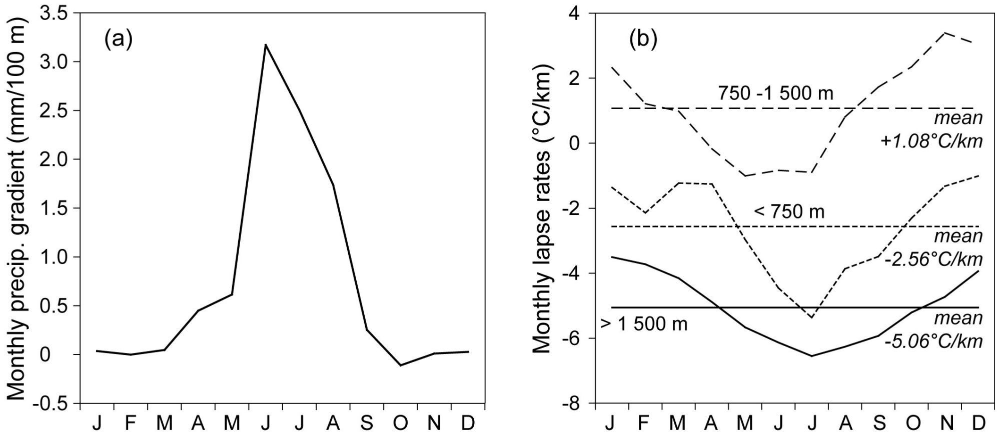


**Fig. 3** Monthly mean lapse rates for (a) precipitation and (b) temperatures as computed from the meteorological stations used (see Fig. 1) over 1976–2011.

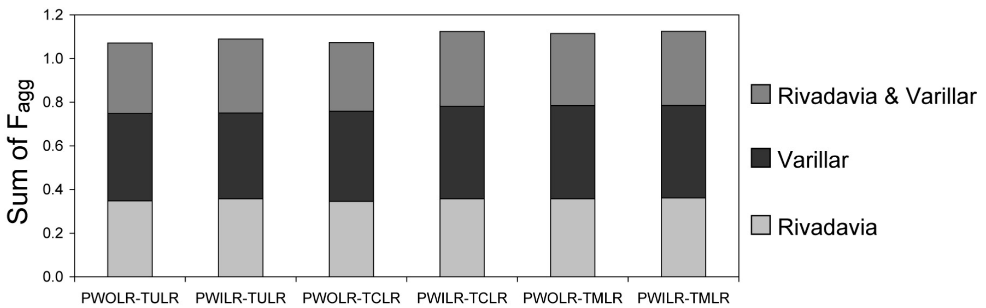


**Fig. 4** Sum of the multi-objective function $F_{agg}$ for all combinations of climate datasets according to the three catchment portions considered.

## RESULTS AND DISCUSSION

### Ranking of the various datasets

Analysis of the sum of the multi-objective function $F_{agg}$ obtained for each catchment according to the six climatic datasets shows no clear superiority of one dataset compared to the others (Fig. 4). Values ranged from 1.072 with the PWOLR-TULR dataset to 1.125 with the PWILR-TMLR one. This indicated that: (a) the hydrological model can compensate for differences in the datasets by adjusting its parameters during the calibration process; and (b) climate inputs based on a constant, universal lapse rate of –6.5°C/km for temperature and that do not account for elevation effects on precipitation (PWOLR-TULR, Fig. 1), are sufficient to simulate discharge accurately. The PWOLR-TURL dataset was thus retained for the rest of the result analysis.

### Model efficiency according to the best-performing dataset

Analysis of the fit of the hydrological model shows that discharge is simulated with a fair degree of realism, as shown in Fig. 5 at the outlet of the Claro basin. The snowmelt regime, which is characterized by a nearly 4-month delay between precipitation and discharge, is reproduced accurately by the model, with a NSE coefficient of 0.88, a bias close to null and a mean annual volume error of 20%. These simulations at a daily time step can be seen as very satisfactory given the significant hydro-climatic variability over the period considered (1981–2011). However, it should be noted that the model tends to underestimate low flows between April and August (Fig. 5(b)). This can be explained notably by the weight given by the multi-objective function to the agreement of peak flows and runoff volumes.

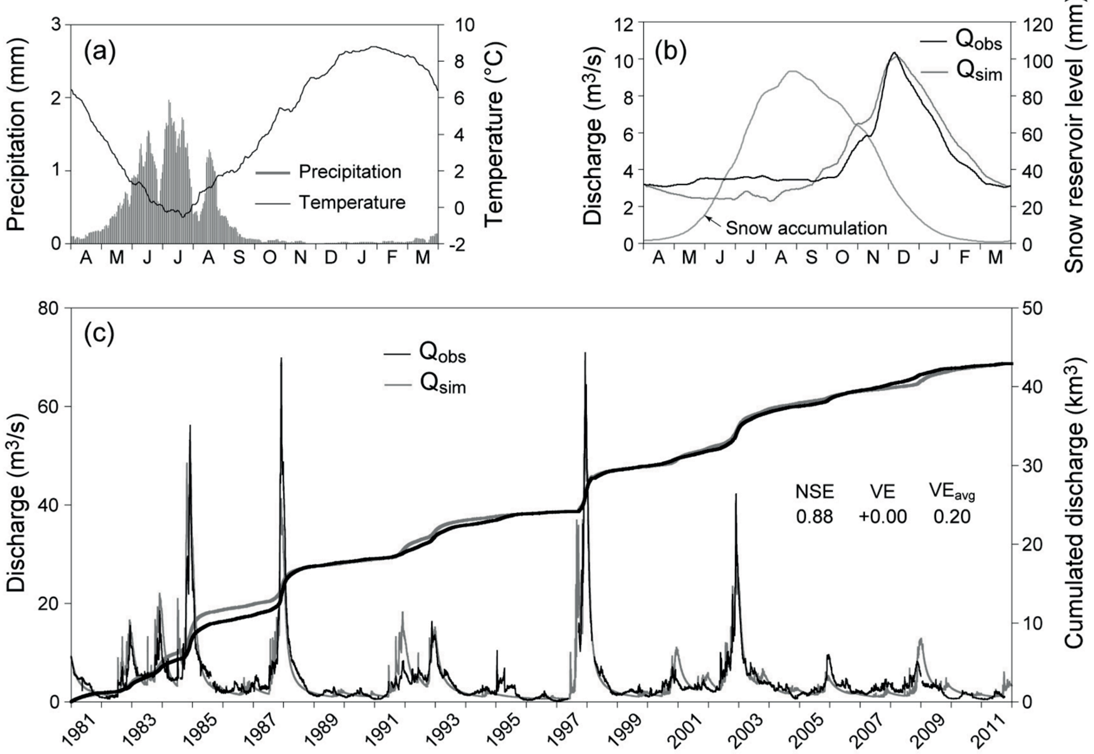


**Fig. 5** Model efficiency at Rivadavia according to the simulations based on the PWOLR-TULR dataset over 1981–2011: mean seasonal variations (a) in climate forcings and (b) in observed *vs* simulated discharge; (c) observed *vs* simulated inter-annual hydrographs.

### Analysis of the calibrated parameters

The calibrated parameters can be very different for the same dataset over each of the three catchment portions (see Table 1), or when considering the different datasets for the same catchment portion. Even if the model compensates for the differences between the input datasets, this raises the well-known issue of equifinality in hydrological modelling, where conceptual parameters have a limited physical meaning and can result from numeric solutions having little link with reality.

The parameters associated to the snow module are rather stable. For instance, the parameters that control snow accumulation as a fraction *x7* of precipitation below a temperature threshold *x6*, are similar for each catchment, with values ranging from 84.1–91.3% and 5.3–6.7°C, respectively. Although *x6* is above the freezing temperature as a result of the climatic inputs being averaged over the entire catchment, its combination with *x7* allows annual snowfall to be estimated at the basin scale (85–90% of total annual precipitation on average depending on the sub-catchment). The *x5* coefficient, which serves to limit the role of PE, also presents similar and very low values (5.0–11.9%) for each catchment. These values indicate the necessity to limit the reference PE in this semi-arid area, where only irrigated valley bottoms have vegetation. In contrast, the parameters controlling the production and routing functions in the GR4j model (e.g. *x1* and *x3* in Table 1) show drastic differences between the catchment portions. This probably results from a model over-parameterization, which can lead to the existence of different parameter sets providing equally good matches.

**Table 1** Calibrated parameters for each catchment according to the PWOLR-TULR dataset.

| Catchment portion | *x1* (mm) | *x2* (–) | *x3* (mm) | *x4* (day) | *x5* (%) | *x6* (°C) | *x7* (%) | *x8* (%) |
|---|---|---|---|---|---|---|---|---|
| Rivadavia | 11 | 2.7 | 473 | 10 | 11.9 | 6.7 | 84,1 | 1.0 |
| Varillar | 1005 | –1.5 | 16 | 12 | 5.0 | 4.2 | 91.3 | 0.6 |
| Riva. & Var. | 517 | –2.1 | 63 | 3 | 5.0 | 5.3 | 85.1 | 0.8 |

## CONCLUSIONS AND PROSPECTS

This study analyses the sensitivity of a hydrological model to different ways of interpolating climate forcing in mountainous areas. This issue is investigated in a context of data scarcity over the upper Elqui catchment in the Chilean Andes. Results show that a dataset based on a basic, constant lapse rate of –6.5°C/km for temperature and no elevation effects for precipitation is sufficient to accurately simulate discharge and the snowmelt regime of the catchment over the last 30 years at a daily time step. Indeed, through a calibration procedure, the hydrological model is able to compensate for the differences (or errors) between the considered input datasets, remaining relatively insensitive to volumetric and spatial differences. On the other hand, analysis of the calibrated parameters reveals convergence problems that cannot be overcome by the sophisticated method proposed for optimization using only the outlet discharge. Since additional data are critically lacking for parameterization, a solution could consist of limiting the number of parameters by using a simplified version of the model. This improvement is currently being considered in order to use the best-performing dataset in an integrated modelling chain aimed at forecasting the capacity of the hydro-system to meet irrigation water needs for viticulture under climate and anthropogenic variability.

## REFERENCES


Groisman, P. & Legates, D. (1994) The accuracy of United States precipitation data. *Bull. Am. Meteorol. Soc.* 75, 215–227.

Nelder, J. A. & Mead, R. (1965) A simplex method for function minimization. *Comput. J.* 7, 308–313.

Oudin, L., Hervieu, F., Michel, C., Perrin, C., Andreassian, V., Anctil, F. & Loumagne, C. (2005) Which potential evapotranspiration input for a lumped rainfall-runoff model? Part 2: towards a simple and efficient potential evapotranspiration model for rainfall–runoff modelling. *J. Hydrol.* 303, 290–306.

Perrin, C., Michel, C. & Andreassian, V. (2003) Improvement of a parsimonious model for streamflow simulation. *J. Hydrol.* 279, 275–289.

Rosenbrock, H. H. (1960) An automatic method of finding the greatest or least value of a function. *Comput. J.* 3, 175–184.

Ruelland, D., Ardoin-Bardin, S., Billen, G. & Servat, E. (2008) Sensitivity of a lumped and semi-distributed hydrological model to several methods of rain interpolation on a large basin in West Africa. *J. Hydrol.* 361, 96–117.

Ruelland, D., Brisset, N., Jourde, H. & Oyarzun, R. (2011). Modelling the impact of climatic variability on the groundwater and surface flows from a mountainous catchment in the Chilean Andes. In: *Cold Regions Hydrology in a Changing Climate* (ed. by Daqing Yang), 171–179 (Proc. 25th IUGG General Assembly, Melbourne, Australia, 28 June–7 July 2011). IAHS Publ. 346. IAHS Press, Wallingford, UK

Ruelland, D., Ardoin-Bardin, S., Collet, L. & Roucou, P. (2012). Simulating future trends in hydrological regime of a large Sudano-Sahelian catchment under climate change. *J. Hydrol.*, 424–425, 207–216.

Sevruk, B. (1997) Regional dependency of precipitation–altitude relationship in the Swiss Alps. *Clim. Change* 36, 355–369.

Sinclair, M., Wratt, D., Henderson, R. & Gray, W. (1997) Factors affecting the distribution and spillover of precipitation in the Southern Alps of New Zealand – a case study. *J. Appl. Meteorol.* 36, 428–442.