Factors Affecting the Distribution and Spillover of Precipitation in the Southern Alps of New Zealand—A Case Study

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ABSTRACT

Rain gauge, radar, and atmospheric observations during a prolonged northwesterly storm in November 1994 have been used to study factors influencing the distribution of precipitation across the Southern Alps. Despite the persistent northwesterly flow, the location and intensity of precipitation varied markedly during this storm, providing an excellent dataset for these investigations. Data from 36 recording gauges in the northern half of the Alps were supplemented by data from 57 daily gauges, which were partitioned into 6-h values. These data were grouped according to distance from the alpine divide, and best-fit transect curves, normalized for rainfall intensity, were established every 6 h. The fraction of the total transect precipitation falling in leeside catchments varied between 0.11 and 0.70, while a “spillover distance” index varied between 6 and 29 km. Comparison with atmospheric profiles of temperature and wind from Hokitika on the west coast of New Zealand and with European Centre for Medium-Range Weather Forecasts analyses revealed that precipitation was confined upwind of the divide during a period of blocked flow near the start of the storm, and only extended into leeside catchments with the onset of stronger flow and reduced static stability. Regression equations involving these factors explained up to 93% of the spillover variations. It is suggested that ascent and precipitation maxima are shifted upstream during blocked flow, while spillover is enhanced during stronger and/or unstable flow as the upstream influence lessens and snow and ice particles drift farther downwind before falling below the freezing level. Further case and modeling studies are needed to demonstrate the wider applicability of these findings.

1. Introduction

It is well known that huge spatial variations in precipitation are found near mountainous terrain. Rainfall is generally enhanced about and upstream of mountain barriers, with a rain-shadow region to the lee. The Southern Alps of New Zealand (NZ), which rise to more than 3000 m (see Fig. 1), exert a huge influence on average rainfall patterns. Because NZ lies within the northern flank of the climatological Southern Hemisphere westerlies, a large gradient of rainfall occurs across this topographic barrier. For example, the mean annual rainfall at locations on the west coast of the South Island is 2–5 m, rising to a maximum of around 12 m in the mountains before declining rapidly to below 1 m on the eastern edge of the Alps (Griffiths and McSaveney 1983).

Most of the precipitation in the Southern Alps occurs during strong northwesterly flow (Chinn 1979), when air has near-normal incidence to the alpine barrier and contains abundant moisture. Although the time-averaged spatial distribution of precipitation is well documented for NZ (e.g., New Zealand Meteorological Service 1984; Griffiths and McSaveney 1983; Salinger 1980; Tomlinson and Sansom 1994), less is known about how this rainfall varies from storm to storm and within individual storms. In nature, precipitation intensity and distribution can vary markedly on substorm timescales, with shifts in the location of the heaviest rainfall relative to the divide. Because headwater basins are so steep and devoid of dense vegetation, the rivers draining the Alps respond quickly to fluctuations in rainfall intensity on these substorm timescales.

In this study, we will analyze the spatial variability of rainfall in the Southern Alps during a prolonged northwesterly storm in November 1994 and relate these variations to meteorological factors. During this storm, the fraction of rain spilling over the divide varied between about 12% and 70% of the total. As precipitation spillover during northwesterly storms supplies most of the water in rivers draining the populated eastern side of the Alps (Ryan 1987), understanding the factors that control spillover variations is a primary concern for optimal management of water resources and hydroelectric schemes east of the divide.

A collaborative research programme called SALPEX (the Southern Alps Experiment) is now underway to improve our understanding of the influence of the Southern Alps on New Zealand’s weather and climate...
During 5–9 November 1994, a major northwesterly storm occurred during a SALPEX field observational campaign. This event was dubbed the “Guy Fawkes storm” in view of NZ’s annual 5 November fireworks commemoration of Guy Fawkes’s conspiracy to blow up the British Parliament in 1605. This storm brought heavy rain and strong winds to many parts of NZ, with 5-day rainfall totals exceeding 1300 mm in places near the main South Island alpine divide, the locus of interest for the present study. Several sites in the Southern Alps recorded more than 160 mm in just 6 h. This lengthy episode of northwesterly rain provided a unique opportunity for studying the factors controlling variations in precipitation distribution across the Alps.

An impressive feature of this storm was the variability in rainfall distribution relative to the Alpine divide. For the first 1–2 days, data gathered from 123 gauges within 80 km of the Southern Alps revealed that rainfall was almost totally confined to the windward (west) side of the Alps. However, from about 1200 UTC 5 November, rainfall began to spill over into leeside catchments, until by 8 November nearly three-quarters of the total rainfall fell to the east of the alpine crest. Both rainfall and spillover declined again during 8 and 9 November.

One goal of this case study is to understand meteorological factors that control these spillover variations and to illustrate some approaches that could be useful in other mountainous regions. The spillover variations are regressed against parameters constructed from European Centre for Medium-Range Weather Forecasts (ECMWF) analyses to assess the potential of deriving simple predictive relations for estimating spillover from operational NWP model output.

In the next section, a synoptic overview of the Guy Fawkes storm is presented. Section 3 describes how rain gauge data are used to construct 6-h precipitation transects across the Alps. In section 4, spillover indices derived from these transects are related to meteorological parameters computed from rawinsonde measurements at Hokitika, New Zealand, upwind of the mountains (Fig. 1) and from analyses prepared by the ECMWF. Concluding remarks in section 5 complete this work.

2. Overview of meteorological conditions

The synoptic evolution of the Guy Fawkes storm over the Southern Alps is seen with the aid of mean sea level (MSL) pressure and 500-hPa charts, surface observations, and wind time sections from Hokitika (HK). The MSL (Fig. 2) and 500 hPa (Fig. 3) contour plots were prepared from ECMWF global model analyses on a 2.5° × 2.5° latitude–longitude grid. Wind isotachs (shaded) are included, along with frontal positions in Fig. 2, obtained from the Meteorological Service of New Zealand operational manual analyses.

The MSL charts depict a strengthening northwesterly flow over NZ ahead of a slow-moving, amplifying trough in the Tasman Sea. Charts at intermediate times (not shown) revealed that the low-level flow impinging on the Alps was northwesterly throughout the period 4–8 November and exceeded 25 m s⁻¹ on 6 and 7 November. However, on 9 November the trough finally passed to the east of the South Island, spreading a cooler westerly flow onto NZ.
Synoptic charts at 500 hPa (Fig. 3) revealed a trough in the Tasman Sea that intensified as a wind speed maximum advanced from the southwestern quadrant. This jet stream propagated through the upper trough before crossing NZ during 7 and 8 November. As it did so, 500-hPa northwesterlies exceeded 55 m s$^{-1}$ at several NZ stations at 1800 UTC 7 November and 0000 UTC 8 November. Climatological records (NZ Meteorological Service 1984) show that, at this level, winds of this strength occur less than 0.1% of the time.

The accompanying surface weather conditions are shown in Fig. 4, which shows time series constructed from hourly surface observations of temperature, dewpoint, wind, pressure, and rainfall for Hokitika and Christchurch (CH). Hourly rainfall from two additional recording rain gauges, located at Arthur’s Pass (Fig. 4f) on the alpine divide about 50 km inland from HK and Ashley Gorge (Fig. 4l), nearly 60 km east of the divide (see Fig. 1), are appended below the HK and CH data.

At HK, about 50 km upwind of the divide, the surface wind was from between north and northeast, backing to the northwest and west during 7 November and again late on 8 November (Fig. 4b). Northeasterlies at HK during northwesterly events suggest that low-level air is blocked by the alpine barrier and constrained to move parallel to it rather than traversing the divide directly. In the Alps, these “barrier winds” are best developed upwind of higher mountains under conditions of high static stability and moderate upstream wind speed (Revell 1994).

The onset of heavy rain at both HK (Fig. 4e) and Arthur’s Pass (Fig. 4f) on 5 November coincided with a sharp increase in surface wind speed at HK (Fig. 4c). From 6 November, rain had largely eased at HK, but continued almost incessantly at 10–15 mm h$^{-1}$ at Arthur’s Pass in the mountains, resulting in much larger rainfall totals there. Because of its location on an upwind coast, air reaching HK is almost certainly derived from the Tasman Sea, as suggested by the negligible diurnal temperature variation in Fig. 4a. This makes HK a suitable location for sampling the air mass impinging on the Alps. Local conditions, of course, are influenced by the proximity of the Alps downwind. No observations were available from offshore locations in the Tasman Sea.
In contrast, CH to the lee of the Alps experienced dry, warm, föhn conditions until the middle of 6 November (Fig. 4g). These conditions are typical of blocked northwesterly flow (Ryan 1987). Temperatures were several degrees warmer than the incoming air at HK (Fig. 4a) and exhibited a marked diurnal cycle, topping 25°C near the time of maximum solar elevation on both 5 and 6 November. This lee warming is due to a combination of sinking motion caused by the blocking of low-level air by the mountains, the release of latent heat as moist air ascends the barrier, and solar heating (Smith 1979). In contrast with HK, the presence of a strong diurnal signal in Fig. 4g in phase with solar heating suggests that the air reaching CH had passed over inland regions warmed by the sun. However, from the middle of 6 November, these warm, dry, föhn conditions to the lee of the Alps gave way to episodes of rain (Figs. 4k,l), cooler conditions, and reduced diurnal variation. Such rain at CH during northwesterlies is a rare event (Hill 1961). One goal of this study is to determine causes of rainfall extending so far to the lee of the alpine barrier.

The temporal evolution of airflow characteristics at Hokitika is seen in Fig. 5. The time–height wind section (Fig. 5a) shows persistent northwesterlies at all levels above 850 hPa until 9 November, when the flow turned to the southwest. Winds aloft strengthened from 6 November as the upper jet crossed NZ (Figs. 3c,d). The upper flow above HK reached a maximum of 93 m s⁻¹ near 300 hPa at 1800 UTC 7 November. Later in this study, we will show how this wind maximum influenced the rainfall distribution to the lee of the Alps. Near the surface, the change from northeasterly along-barrier flow to northwesterly flow early on 7 November suggests a change from strongly blocked flow to unblocked flow where air directly ascends the Alps. Despite missing information, the time–height section of potential temperature (Fig. 5b) depicts a period of cooling and lowering of the freezing level on 7 November, accompanied by a decrease in static stability. This destabilization occurs in conjunction with the change from northeasterly barrier flow to northwesterlies on 7 November (Fig. 5a).
3. Transect and spillover analysis

In this section, we describe a methodology for constructing rain gauge transects across the alpine divide and using these to obtain 6-h estimates of spillover during 4–9 November 1994. The resulting spillover indices are compared with radar-based spillover estimates.

a. Rainfall data

Data from 133 stations in the central South Island (Fig. 6) were used. These comprised 50 recording gauges (mostly tipping bucket)—8 along the Waimakariri River marked with a “W” plus 42 others marked with an “A”—and 83 gauges recording 24-h totals, read at 0000 UTC on the UTC date (0900 NZDT1 the day after). Data from the recording gauges were accumulated into 6-h bins centered on 0000, 0600, 1200, and 1800 UTC daily (i.e., ending at 0300, 0900, 1500, and 2100 UTC)

1 NZDT—New Zealand daylight time—is 13 h ahead of UTC.
Fig. 5. (a) Vertical wind time section for Hokitika. Dates (November 1994) are indicated along the top, with hours (UTC) along the bottom. Winds are plotted as in Fig. 3. (b) As in (a) except with potential temperature every 2.5 K, drawn from temperature soundings at the times indicated along the bottom. The freezing level is shown as a thick line.

Individual gauge observations are subject to considerable measurement uncertainty. Gauges tend to systematically underestimate true precipitation, chiefly because of wind effects near the gauge orifice. This is especially so in mountainous terrain, where these biases can be as high as 40% (e.g., Groisman and Legates 1994). Uncertainty also arises from variable gauge exposure and the statistically small sample area (Sevruk 1975, Rodda 1971, Seed and Austin 1990). In addition, natural precipitation variability is caused by embedded convection and topographically induced eddies.

Despite this uncertainty, it is generally possible to resolve coherent spatial features from time-averaged
precipitation fields (e.g., Sinclair 1993, 1994). In Fig. 7, a contour analysis of 123 24-h gauge totals is used to depict rainfall distribution and intensity variations during this storm. Data from the recording gauges were incorporated by summing them into 24-h totals ending 2100 UTC. The successive correction scheme of Cressman (1959) was used to analyze the irregularly spaced data on a regular 10-km Lambert conformal grid for contouring. The Cressman scheme weights each observation within some distance \( r_o \) (called the radius of influence) of each grid point by weights \( W = \frac{1}{2} \left( 1 - \frac{r}{r_o} \right)^2 \) that decrease in Gaussian-like fashion with increasing distance \( r \) between the grid point and the observation. Selecting \( r_o \) is a compromise between at-
tempting an overly close fit to uncertain data for small \( r \) and blurring realistic detail for larger values. A radius of influence of 20 km was selected to preserve coherent detail down to about 10–15 km. For the analyses in Fig. 7, the rms difference between the gauge values and the Cressman analyzed data interpolated to the gauge location was close to 7% of the maximum value for each of the six times shown.

Despite the spatial averaging inherent in this analysis, Fig. 7 reveals considerable variability in rainfall intensity and distribution during the storm. Rainfall on 4 November (Fig. 7a) was largely confined to the upwind side of the Alps, with a sharp cutoff just east of the alpine divide (the solid line, as in Fig. 6). During 5 and 6 November (Figs. 7b,c), both rainfall intensity and spillover increased, with the maximum rainfall straddling the divide during 6–8 November (Figs. 7c–e). During this period, rainfall extended far to the east of the divide, with the 10-mm contour actually reaching the east coast on 7 November (Fig. 7d).

This contour analysis of daily totals gives a general overview of rainfall intensity and distribution variations over the Alps during the Guy Fawkes storm. More sophisticated rainfall mapping approaches, such as cokriging (e.g., Phillips et al. 1992; Hevesi et al. 1992), based on elevation and location may provide more realistic rainfall estimates from which precipitation spillover indices could be derived. Here, however, we use a simple approach that takes advantage of the near two-dimensional nature of the rainfall fields in Fig. 7 and arranges gauge data as a function of distance (upwind and downwind) from the divide. Spillover indices are then derived directly from these 2D accumulation–distance transects.

This approach is only valid in linear mountain chains like the Southern Alps, where the expected value of the precipitation field depends on the distance along the transect and where departures from this expected value represent random fluctuations. Two-dimensional transects have been extensively used in the southern Alps for analyzing climatological rainfall (Griffiths and McSaveney 1983; Chinn 1979) and storm rainfall (Henderson 1993).

The remainder of the analysis is confined to gauges in the northern half of the Alps (above the marked line in Fig. 6) in order to reduce the effect of nonrandom variations along the approximate 450-km length of the alpine divide. This reduced gauge numbers used from 133 to 93 (57 daily and 36 recording).

b. 6-h partitioning

The aim of this study is to resolve shorter-term variations in rainfall distribution across the Alps and to relate these changes to meteorological factors measured every 6 h. Longer-term rainfall accumulations like daily totals are less representative of instantaneous airmass characteristics. Rainfall transects were therefore analyzed every 6 h. Unfortunately, just 36 of the 93 gauges measured 6-h totals. However, data from the remaining 57 sites measuring daily totals were incorporated by partitioning them into 6-h values based on nearby recording sites.

This partitioning was accomplished as follows. Time series for the recording gauges were first plotted (Fig. 8), grouped in four bands: stations greater than 5 km upwind from the divide, stations near the divide (between 5 km upwind and 10 km downwind), stations 10–25 km downwind, and stations greater than 25 km downwind. This grouping resulted in series within a band having similar temporal variations. For example, most sites upwind of the divide (first column of Fig. 8) recorded similar peaks at 1800 UTC 4 November, 1800 UTC 5 November, 1200 UTC 8 November, and 0000 UTC 10 November. Differences between individual series reflect a combination of measurement uncertainty, natural precipitation variability, and local topographic influences. As an extreme example, sites A8 and A9, only 2 km apart, recorded widely differing 24-h totals of 124 and 313 mm, respectively, on 7 November.

Next, the mean series for each band (bottom of each column in Fig. 8) was used to split each 24-h gauge total into four 6-h values. These four values were assigned in proportion to the mean series for that day for the band containing the 24-h station. For example, for an upwind 24-h site on 5 November, the largest (smallest) rainfall was ascribed to 1800 (0600) UTC. Within the last band (more than 25 km downwind), where the relation between individual sites in Fig. 8 appeared weak, daily totals were simply split into four equal parts. Figure 9 shows the result of this partitioning for all daily gauges in the first band (more than 5 km upwind from the divide). These “reconstructed” series were similar to those from the recording gauges in the first column of Fig. 8. For example, the reconstructed series for stations D51, D52, and D57–D61 (Fig. 9), all clustered more than 20 km upwind of the divide near its north end, are characterized by a dominant peak at 1200–1800 UTC 5 November, strikingly similar to the series for automatic station A1 (Hokitika) in Fig. 8, the only recording gauge more than 20 km upwind from the divide. Likewise, reconstructed series for D54 and D65–D68 have a double peak on 4 and 5 November, similar to the group of automatic gauges A11, A12, and A13 located south of the previous group. Station D56 has a noticeably different series as a result of recording no rainfall on 4 and 5 November, the only station west of the divide to do so. It is tempting to speculate that this gauge was not read on these two weekend days.

Clearly, this partitioning of 24-h totals is most believable when time series are similar at a number of closely spaced sites. The 6-h averaging period is a compromise between reducing the noise from transient small-scale fluctuations (e.g., individual spikes in the hourly rainfall records in Figs. 4e,f,k,l) and preserving more persistent and spatially coherent features that oc-
Fig. 8. Time series of 6-h rainfall accumulation (mm) obtained from recording gauges, grouped in four bands based on distance to the alpine divide. Individual axes are scaled as indicated, and the mean series for each band is shown at the bottom of each column.

cur at a number of stations. At the 6-h resolution used, a coherent precipitation feature moving at just 10 m s$^{-1}$ can easily transit the entire study domain, thus making a near-simultaneous contribution at each station affected.

c. Transect analysis

This extended database of 36 recording gauges, augmented by reconstructed 6-h data from the 57 daily gauges, formed the basis for the transect analysis. Data from these 93 sites were first arranged as a function of distance along a transect normal to the divide. For each gauge, the displacement $d$ from the alpine divide was determined as the shortest distance to any point on the alpine divide, negative (positive) for gauges west (east) of the divide. These values were then displayed as points in a series of 6-h normalized rainfall $R$ versus $d$ plots (Fig. 10). Rainfall data were first normalized for each time by dividing by the mean of all the observations (indicated in the top right) and the axes scaled so that the top corresponds to seven times this mean, marked by a horizontal line. This scaling enables variations in rainfall distribution to be analyzed independently of intensity changes. The solid curves in Fig. 10 are curves of best fit to the $R$–$d$ pairs, obtained by means of Cressman analysis in one dimension using a grid spacing of 2.5 km and a radius of influence of 15 km. This preserves coherent detail in $R$–$d$ variations down to about 10 km.

Figure 10 reveals that individual observations are displaced from each best-fit transect. This scatter can arise from natural variability and measurement uncertainty (including errors associated with partitioning the 24-h data) and the spatial averaging used to obtain the transect. There would also be systematic departures from
each transect arising from differing locations along the divide and other persistent local effects. The variation of this scatter with time was examined by computing the mean absolute value of the departures for each best fit curve as a fraction of the mean rainfall and plotting as a function of time (Fig. 11). Reduced scatter averaging around 0.5 of the mean during 1200 UTC 5 November to 1800 UTC 8 November coincided with the heaviest rain. A poor fit early in the storm occurred during marginal precipitation, when a number of stations in Fig. 10 reported zero rainfall, while the increased scatter later on 9 November coincided with the appearance of convective cells in satellite imagery (not shown). This brief analysis of scatter suggests that arranging rain gauge data into a transect is most meaningful where precipitation is both widespread and non-convective. It is also recognized that the statistical characteristics of the reconstructed records are not the same as the actual 6-h records. Because the reconstructed records are based on averages of several 6-h records, their variability from a mean transect is probably somewhat reduced.

Some stations were found to be persistently above (or below) each normalized best-fit line, possibly due to local topographic effects or location along the divide. To assess the likely contribution from these systematic effects, we removed their effect by computing the average (signed) departure for each station for the curves in Fig. 10. This was obtained as a fraction of the mean and then subtracted from each observation. The transect curves were then recomputed (not shown, but very similar to Fig. 10 with less spread) and the mean, normalized, absolute departure from them obtained as described above. This yielded an approximate 25% reduction in the scatter during the middle of the storm (the lower curve in Fig. 11). The remaining 75% of the scatter is due to the natural, measurement, and processing uncertainties noted earlier. During 9 November, the systematic component of scatter vanishes, consistent with random convective precipitation.

The rainfall transects in Fig. 10 reveal marked variations in the sharpness and location of the rainfall maxima relative to the divide. Frequently, over half the total precipitation fell in a narrow alpine zone under 40 km in width. The location of this peak varied from 20 to 30 km upwind of the divide on 4 November to a few kilometers downwind from it at times on 6–8 November. These variations have a major influence on the fraction of total runoff occurring in leeside catchments.

The peaks also indicate a remarkable degree of orographic precipitation enhancement in the Alps. For example, during the period 0000 UTC 6 November–1800 UTC 8 November, when rainfall well upwind from the divide was clearly nonzero, the ratio of the peak transect rainfall to the average rainfall measured at locations more than 30 km upwind (not shown) varied between 8 and 22, and averaged 13. These large enhancement ratios stem partly from the greater proportion of the time that rain is observed in the Alps compared with nearer the coast. This is seen by contrasting the hourly rainfall
Fig. 10. Six-hourly transects of rainfall across the Southern Alps as a function of distance (km) from the divide at the indicated times (UTC). The upwind direction is to the left. The solid lines are a fit to the individual observations, marked as dots, and the top of each plot corresponds to seven times the mean transect rainfall, marked by a horizontal line. The vertical line marks the alpine divide, while the maximum and mean rainfall for each 6-h period are indicated in the top right-hand corner.
time series from Hokitika (Fig. 4e) on the coast with Arthur's Pass (Fig. 4f) in the mountains.

A mean rain gauge transect for the whole storm (Fig. 12) was obtained by averaging the 27 normalized graphs in Fig. 10. This means that contributions from individual transects were similar, regardless of actual rain amount. The resulting mean transect was broader than most of the individual curves in Fig. 10, with a mean enhancement of just over 5. This storm-average enhancement factor is substantially less than that observed at individual times, especially during 6–8 November, when the enhancement factor averaged 13 and peaked at 22. Incidentally, departures by individual stations from the mean transect in Fig. 12 represent the systematic error removed to get the lower curve in Fig. 11.

In comparison with the transects in Fig. 10 and even in Fig. 12, time-averaged transects for annual precipitation (e.g., Griffiths and McSaveney 1983) are broader and flatter because both intra- and interstorm fluctuations are averaged out. For example, the ratio of the 12-m peak annual precipitation near the divide to the mean annual total of 2.824 m at Hokitika (Tomlinson and Sansom 1994) is only about 4.2 (cf. the storm average enhancement factor of 5.46 and peak of 22).

d. Spillover analysis

The spillover fraction was obtained every 6 h from the solid lines in Fig. 10 by dividing the sum of best-fit estimates downwind of the divide by the sum of all best-fit estimates. This estimate was made only for times when the transect mean rainfall in Fig. 10 exceeded 5 mm. This threshold for inclusion omits a few times having marginal precipitation near the start and end of the series. The resulting time series is shown in the top curve of Fig. 13. The variations in spillover during the course of the storm reflect shifts in the location and shape of the rainfall peaks in Fig. 10. At the start of the storm on 4 November, as little as 11% of the rainfall was spilling across the divide before increasing to a maximum of more than 70% at 1800 UTC 7 November and 0000 UTC 8 November. The spillover fraction subsequently decreased again.

The lower curve in Fig. 13 is a “spillover distance,” computed as $\Sigma d R_{i} / \Sigma R_{i}$, where the summation is over all rainfall observations $R_{i}$ to the lee of the Alps at a distance of $d_{i}$ (>0) from the divide. It is equivalent to the distance downwind from the divide within which half of the leeside precipitation falls. Its evolution, while similar to that for spillover fraction, is somewhat smoother. On 4 November, half of the leeside rainfall occurred within 8 km of the mountains. However, by 1800 UTC 7 November, the spillover distance extended to 28 km. At this time, more than 20% landed more than 40 km downwind (not shown). The spillover distance decreased again after that.

The spillover variations in Fig. 13 were subjectively
compared with radar-based estimates (Fig. 14). The New Zealand Meteorological Service operates an Ericson weather surveillance radar at Rakaia, near the east coast of the South Island just south of Christchurch (see Fig. 1). This radar cannot see right into the mountains because of beam blocking by the foothills to the east of the Alps. However, for this northwesterly storm, rainfall extended east of these foothills, providing useful data on cross-alpine spillover. The processed radar plan position indicator (PPI) accumulations were manually analyzed to estimate the distance to which precipitation echoes extended downwind of the Alps. Results (Fig. 14) fluctuated somewhat, but suggested reduced spillover on 4 November followed by an increase in the downwind extent of precipitation during this storm. The large dip early on 6 November coincided with a temporary decrease in precipitation intensity at Arthur’s Pass and Ashley Gorge (Figs. 4f,l), which may have made precipitation detection by radar more difficult at this time. Otherwise, results are broadly consistent with the temporal evolution of spillover distance in Fig. 13. Differences arise because of the limited domain “visible” to the radar, the different spillover measure used, and the subjective nature of PPI interpretation.

4. Comparison with meteorological data

To assess the factors that might influence spillover, a variety of meteorological parameters were regressed against the spillover fraction and distance series in Fig. 13. These parameters were derived both from HK rawinsonde measurements and from 12-h ECMWF analyses interpolated to HK. A variety of parameters including freezing level and wind velocity, static stability, and temperature in various layers were tested. Spillover was found to increase with wind speed and decrease with increasing static stability, temperature, and freezing level. However, when averaged over the two data sources, no single factor explained more than about 60% of the observed spillover variance.

One hypothesis that emerged from this preliminary analysis was that spillover was controlled by the extent of hydrometeor drift downwind of the divide. To test this, we compared spillover with the component of wind normal to the divide averaged above the freezing level \( V_{fz} \) (top curve in Figs. 15a,b). Because solid precipitate falls at only about 1 m s\(^{-1}\) compared with 4–7 m s\(^{-1}\) for rain (Sarker 1966; Collier 1975), we would expect the greatest spillover for large \( V_{fz} \). This factor was found to explain 35%–50% of the spillover distance and fraction variations in Figs. 15c,d, which are plotted at times corresponding to the sounding or ECMWF data.

A second factor considered to influence spillover was blocking. When stable air does not directly ascend the barrier, the influence of the mountain propagates upwind, shifting ascent and precipitation maxima upstream as air lifts over the blocked region (Cotton and Anthes 1989) and thus reducing spillover. Also, during blocking, sinking air to the lee of the mountains often has a midtropospheric origin, making it warmer and drier. This enhances leeside evaporation and reduces spillover. The sharp precipitation cutoff near the alpine crest during 4 and 5 November coincided with west coast barrier flow (Fig. 4b) and enhanced static stability (Fig. 5b), conditions indicative of blocking according to Overland and Bond (1995) and many other studies. Later in the storm, increasing spillover coincided with a reduction in static stability and a turning of the low-level flow normal to the mountains, suggesting unblocked flow.

Because a combination of high static stability and low trans-alpine windspeed is conducive to blocking, a “blocking parameter” \( B \) was constructed by dividing the average static stability parameter for the layer below 4000 m by the mean wind speed (m s\(^{-1}\)) normal to the divide in this layer (bottom two curves in Figs. 15a,b). For the HK soundings, \( B \) alone explained 67% and 78% of the spillover fraction and distance variations in Fig. 15c, and 76% and 88% for the ECMWF curves in Fig. 15d. Two-parameter linear regression equations for spillover based on both \( V_{fz} \) and \( B \) explained 75% and 82% of the spillover fraction and distance variability, respectively, for HK sounding data, and 85% and 89% for the ECMWF analyses during the storm. The four spillover estimates based on these regression equations are included in Figs. 15c,d. The signs of the coefficients for each equation implied more spillover for stronger wind aloft and/or less blocked flow, consistent with our expectation from theory.

There was reasonable agreement between the HK observations and the ECMWF analyses, although the latter underestimated the upper-level wind maximum and the static stability decrease on 7 November. However, a bigger fraction of the observed spillover variance was explained by the ECMWF data. It is possible that the HK sounding data included local topographic effects not representative of the wider southern Alps region.

Although the two-parameter regression equations yielded \( F \) statistics exceeding 20, suggesting that the results are statistically significant at better than the 99% confidence level, this does not imply that the regression...
Fig. 15. Time series of mean wind speed above the freezing level and between the surface and 4 km (m s$^{-1}$), and mean static stability parameter $T_\alpha$ ln$u/p$ between the surface and 4 km ($10^{-2}$ m$^2$ s$^{-2}$ Pa$^{-2}$) (a) from the Hokitika sounding and (b) from ECMWF analyses. Observed spillover fraction and distance (solid with dots), along with those predicted from a regression equation (thin line) for (c) the Hokitika sounding and (d) ECMWF analyses. The percentage of explained variance for each spillover estimate is indicated in parentheses.

relationships are directly applicable to other cases. This analysis is clearly limited by its short duration and the consideration of just one northwesterly episode. However, the results have demonstrated that the presence or absence of blocking and the wind profile above the freezing level can be important factors controlling the distribution of precipitation in the Southern Alps.

5. Summary and conclusions

In this study, rain gauge and radar observations have been used to study how the distribution of precipitation across the Southern Alps varied during a prolonged northwesterly storm in November 1994. Observations from 93 gauges were first arranged into 6-h transects for the northern half of the Alps. Data from 36 recording gauges were augmented by partitioning 57 daily gauges into 6-h values. Transects across the Alps were obtained by arranging data from each station as a function of distance from the divide and normalizing for intensity variations in order to focus on just the distribution of precipitation relative to the alpine crest. The fit of individual stations to these transects was generally good, with scatter mostly below 10% of the peak rainfall. This level of scatter suggests that the 6-h averaging period is sufficient to average out noise from localized transient rainfall peaks, yet short enough to retain spatially coherent features occurring on this timescale. Increased scatter during marginal and/or convective precipitation made transects less meaningful at the start and end of the storm. About 30% of the total scatter was systematic, probably arising from differing locations along the divide and other persistent local effects.

The series of normalized transects obtained every 6 h during this storm revealed marked temporal variations in the intensity and width of the rainfall maxima, and in their location relative to the divide. Much of the time, over half of the precipitation fell within a narrow zone less than 40 km wide, located near the divide. At such times, the maximum precipitation was up to 22 times that averaged at locations upwind from the divide and fluctuated in position between 20 km upwind and 5−10 km downwind of the divide. Because of these temporal variations, this degree of orographic enhancement was only evident in transects constructed on intrastorm timescales. A mean transect for the whole storm was much broader, with an enhancement factor of just over 5.

Results from this study suggest that the maximum precipitation during blocked flow can occur more than 20
km upwind from the divide, while during stronger and more unstable flow the maximum can actually occur to the lee. Understanding these shorter-term fluctuations in the location of the maximum and in spillover is critical for accurate flood forecasting, especially in the Southern Alps, where catchment response times are short. The large orographic enhancement factors observed in this study suggest that attempts to interpolate inland rainfall on intrastorm timescales from transects based on longer periods will result in greatly underestimated peak rainfall in the mountains and the misplacement of its location.

During this storm, the fraction of the total precipitation spilling over into leeside catchments varied between 11% and 70%, with a spillover distance index varying between 6 and 29 km. Comparison of these two spillover measurements with observations of temperature and wind from Hokitika on the west coast and with ECMWF analyses revealed that spillover increased with wind speed, but decreased with increases in a blocking index, obtained as static stability below 4 km divided by airflow normal to the barrier in this layer. We propose that this is because blocking occurs in moderate airflows under stable conditions and results in ascent and precipitation maxima being shifted upstream, while strong wind and/or decreased static stability reduce this upstream influence. In addition, an increased component of flow normal to the barrier causes falling hydrometeors to drift farther downwind before landing. A two-parameter regression equation involving the blocking index and wind speed above the freezing level explained up to 93% of the spillover variations during this storm. This regression relationship probably only demonstrates that the blocking and downwind drift of hydrometeors can be important factors controlling rainfall distribution and should be considered in future efforts to build predictive models. However, whether the regression relationships obtained from this exploratory data analysis have any predictive skill when applied to other cases remains to be tested.

We are now extending this study to examine a large number of storms in the Southern Alps during 1980–92. In addition, mesoscale modeling of this and other storms is being used to refine our hypotheses about processes influencing spillover by examining the sensitivity of modeled spillover to upwind meteorological conditions.

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