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Regional and Local Scale Characteristics of Foehn Wind Events over the South Island of New Zealand

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With 12 Figures

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Summary. Regional and local scale windfield and air mass characteristics during two distinct synoptic foehn wind events over southern New Zealand are examined. The Southern Alps were observed to effectively block low level onshore gradient northwesterly airflow and to channel it through both Cook and Foveaux Straits. Blocking of the onshore synoptic northwesterly airstream also resulted in barrier jet formation along the western slopes of the Southern Alps. This feature of the regional windfield has not previously been documented and develops during favourable conditions to a height of between 1500 to 1800 m above sea level. In the immediate lee of the Southern Alps at Lake Tekapo, classic foehn conditions such as warm ambient air temperatures, low relative humidities and gusty winds were monitored throughout both foehn events examined. Differences in the local windfield were however observed, which reflect the importance of local topography on lee side windfield dynamics during foehn events. Spillover of precipitation to the lee of the mountains was monitored in the latter stages of each case study and appeared to be associated with the passage of the cold front over the Southern Alps. Observations made by this investigation have a number of applied and theoretical implications with respect to meso-scale modelling, orographic rainfall distribution and forecasting.

1. Introduction

Historical and contemporary scientific investigation into the thermal and dynamic characteristics of foehn winds spans almost 130 years, with the first broadly correct account of their origin given by Hann (1866). In very general terms, foehn describes a warm dry wind which descends the lee slopes of a mountain range, such as the *south foehn*, north of the European Alps. *Foehn* has subsequently become the most common generic reference to all such winds including the *chinook* of the Rocky Mountains, the *ibe* of Central Asia, the *Zonda* of the Andes and the *berg wind* of South Africa (Brinkmann, 1971).

In the South Island of New Zealand, the local foehn is referred to as the *nor'wester* in reference to its usual direction of origin, the northwest. The *nor'wester* is typically associated with warm ambient air temperatures, low humidities and variable wind speeds, which in many alpine areas may regularly exceed 40 to 50 ms^{-1} (Chinn, 1980; McCracken, 1980; Allan, 1991). However, unlike the European *foehn* and the *chinook* which have been studied extensively during experiments such as ALPEX (Alpine Experiment) and WAMFLEX (Wave Momentum Flux Experiment) respectively (Hoinka, 1985), only limited observational and theoretical studies of the *nor'wester* have been conducted. These have focused on the temporal and spatial characteristics of the *nor'wester* once it leaves the confines of the inner montane basins and river valleys of the Southern Alps and advances across the Canterbury Plains. Such studies include those by Kidson (1932), de Lisle (1969) and Lamb (1972, 1975), while McGowan (1994) is more concerned with foehn conditions within the mountains. As a result, there currently exists a substantial lack of published scientific literature on the regional (meso-α and meso-β (Orlanski, 1975)) and local scale (Oke, 1987) characteristics of the foehn *nor'wester* within the Southern Alps, and over southern New Zealand.

The need for detailed scientific investigation into the physical and temporal characteristics of the *nor'wester* are significant. For example, precipitation spillover during spring northwesterly storms provides valuable inflows into approximately 66% of New Zealand's hydro-electric power generation plant which has a generation capacity of 3290 MW (Justice, 1990). Less frequent foehn events may subsequently result in alpine drought conditions, which during 1991/92 contributed to a national energy crisis. Foehn windstorms because of their thermal and dynamic characteristics, such as low humidities and high wind speeds regularly initiate dust storms within the Southern Alps by effectively drying exposed surface sediments in geomorphically active areas. Over the last decade, wind erosion of the alpine tussock grasslands during foehn windstorms has become a significant environmental problem. It has been suggested that dust storms during foehn windstorms cause health problems amongst residents of alpine villages, while windblown dust seriously threatens the expanding tourism industry of this region (McGowan, 1994). Suggested control techniques, such as the establishment of exotic timber plantations and shelterbelts, may however be inappropriate if silviculture techniques are not designed for those areas subject to very high wind speeds. The planting of trees in river valleys where jetting or channelling can occur, may result in severe damage to shelterbelts and forestry plantations. For example, on the 1st August 1975 a foehn windstorm caused approximately $12 million dollars worth of damage to timber plantations in the Canterbury Province in only a few hours (Bowen, 1981).

This investigation presents observations from the first scientific investigation into foehn characteristics within the central Southern Alps, where foehn windstorms are the most dominant wind regime observed. Both regional scale wind and pressure fields over southern New Zealand are also examined during the two case studies presented to identify regions of orographic blocking, channelling and lee trough development. Results presented have important theoretical and practical applications with regard to the current SALPEX (Southern Alps Experiment) programme (Wratt et al., 1995), forecasting and resource management within the Southern Alps.

2. Physical Setting

The Southern Alps of new Zealand act as a formidable barrier to the mid-latitude westerlies extending from 42 °S to 45 °S with a mean height of between 2500 to 3000 m above sea level (Fig. 1). Onshore west to northwesterly airflow is forced to ascend the Southern Alps, while low level airflow may diverge upwind of the South Island and pass through either Foveaux or Cook Straits (Fig. 1). The forced ascent of the onshore maritime airstream typically produces extensive orographic rain systems along the western slopes of the Southern Alps. As a result, annual precipitation may regularly exceed 10 m in some regions of the South Islands west coast, while in the lee of the alpine divide, rainshadow effects dominate producing a semi-arid environment where annual precipitation is often less than 600 mm.

Field experiments for this paper were conducted at Lake Tekapo, approximately 180 km southwest of Christchurch in the central Southern Alps (Fig. 1) as part of a much larger study into the nature

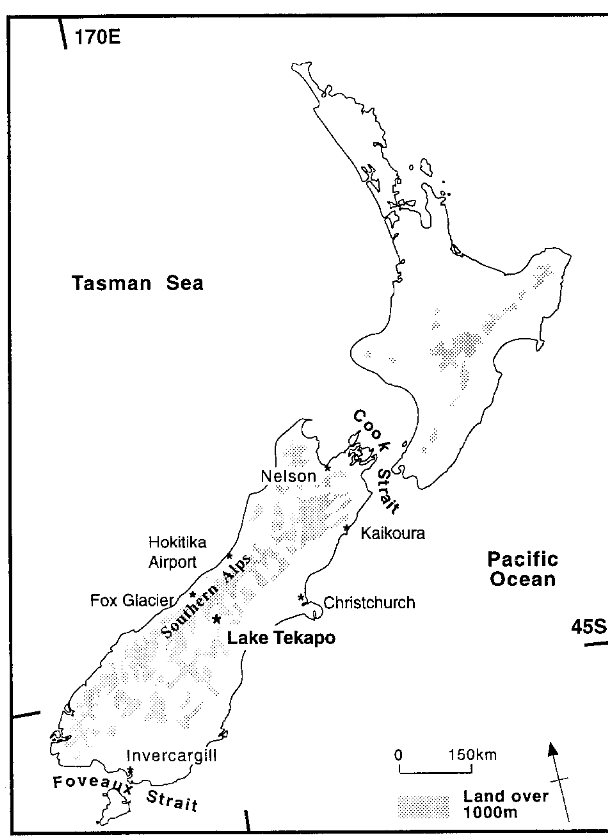


Fig. 1. Location map of New Zealand, with the places referred to in the text indicated

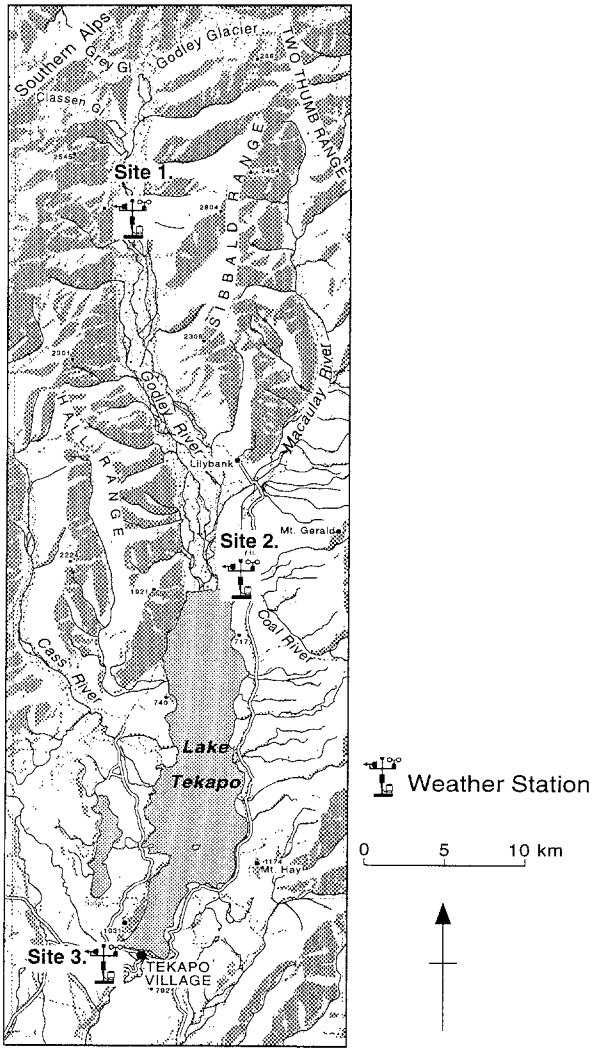


Fig. 2. Location map of the Lake Tekapo study area with the three automatic weather stations indicated

and incidence of windblown dust. Lake Tekapo occupies a glacially excavated rock basin which is blocked at its southern extension by glacial moraine and outwash surfaces on which Tekapo Village is situated (Fig. 2). Immediately east of the lake, the Two Thumb Range extends from the crest of the Southern Alps in a southerly direction along the eastern shoreline of the lake. In the northern region of the study area, the Sibbald and Hall mountain ranges which are eastern extensions of the Southern Alps have many peaks exceeding 2300 meters. These mountains are extensively glaciated and contain sizeable perennial snowfields. Incised into this mountainous region are the Godley and Macaulay River catchments (Fig. 2). Topographically channelled and reinforced foehn northerly airflow within these river valleys may exceed 50 to 60 ms^{-1} (McGowan, 1994) and regularly results in localised dust storms in the absence of precipitation. West of Lake Tekapo lie vast hummocky moraine and glacial till deposits which dip in a southerly direction towards the open expanse of central MacKenzie Basin.

Local vegetation in the vicinity of the lake consists of tussock grassland on the lower slopes of the surrounding mountain ranges and the adjacent lowland areas. The quality of natural vegetation decreases dramatically along the north-south axis of the lake basin in response primarily to the strong north-south precipitation gradient within the catchment. Subsequently, the steep well vegetated mountain slopes near the northern margin of the lake give way to barren greywacke rock scree slopes further south near Mt Hay (Fig. 2).

The climate of the Lake Tekapo area is typical of the inner montane basins of the South Island, where elevation and rain-shadow effects dominate in the absence of a maritime moderating influence on the weather. As a result, annual rainfall averages only 600 mm per year resulting from an average of only 72 rain days (days on which 1 mm or more of rain was recorded). Annual sunshine hours are in excess of 2200 hours, while this region experiences an average daily range in temperature of 11.6 °C (Garr and Fitzharris, 1991).

The wind regime of the Lake Tekapo basin is dominated by light diurnally reversible, thermally driven circulations which dominate under clear anticyclonic conditions, when synoptic pressure gradients are weak. However, foehn west to northwesterly winds are the most common form of surface level gradient airflow, experienced in the study area as a topographically channelled northerly wind, and are usually followed by short periods of southwesterly airflow associated with the passage of a cold front, before clearing weather (McGowan, 1994).

3. Observation Techniques

Observations presented in this paper were made as part of a much larger investigation into windblown dust between October 1991 and March 1993 (McGowan, 1994). Throughout this period three automatic weather stations (sites 1, 2 and 3 in Fig. 2) provided twenty and sixty minute averages of wind speed and direction at 2.65 m, soil and surface air temperatures at − 15 cm and

15 cm respectively, screen air temperature and relative humidity at 2.65 m, solar radiation and totalised rainfall. They were part of a larger meteorological monitoring network installed for the research project. Site 1 within the upper reaches of the Godley River Valley, was located on a river flat at approximately 900 m above sea level, while sites 2 and 3 were located near lake level at an altitude of 720 m.

Vertical soundings of wind speed and direction were obtained from Hokitika Airport (Fig. 1) for the two case studies presented. This site is the only centre to conduct soundings upwind of the Southern Alps during westerly quarter synoptic airflow. Surface wind speed and direction observations and atmospheric pressure recordings from other South Island monitoring sites presented in this paper were obtained from the National Institute of Water and Atmospheric Research.

4. Foehn Wind Events, Lake Tekapo

Onset of foehn wind events are typically identified by a marked increase in ambient air temperature, a corresponding decrease in relative humidity and an increase in wind speed, as outlined by Atkinson (1981). Throughout this investigation foehn wind events were identified using these criteria, while a trans-alpine pressure gradient (west to east) indicating lee trough development must have been present. Two distinctly different synoptic situations will result in these conditions over the South Island of New Zealand. Namely, airflow onto the South Island's west coast may either be of sub-polar or sub-tropical origin depending on air mass trajectories involved. Ryan (1987) suggested that warm moist airflow of sub-tropical origin was more likely to ascend over the Southern Alps than cooler airflow of sub-polar origin. The former is associated with anticyclonically curved motion, with the latter associated with cyclonic curvature. However, no scientific research has been conducted to test Ryan's hypothesis, although empirical studies suggest that more classic foehn conditions are experienced in the lee of the Southern Alps during strong, persistent northwesterly gradient airflow. Barrier jet development has been observed during both synoptic situations suggesting that at low levels anyway, airflow may generally prefer to flow parallel to the Southern Alps rather than to ascend them (McGowan, 1994).

In the following two case studies of South Island foehn wind events, regional and local scale airflow characteristics are presented in association with atmospheric pressure observations. These follow brief reviews of the synoptic scale weather systems which affected New Zealand during each case study. As no individual climate phenomenon is discrete, but is part of a continuum, this allows for the meteorological observations made at Lake Tekapo presented in the subsequent two case studies to be set in context against regional and synoptic scale processes.

5. Event 1: 18th and 19th October 1992

5.1 Synoptic and Regional Windfields

Synoptic analyses for 1200 NZST on the 18th and 19th October 1992 are presented in Fig. 3. Both surface level pressure maps show a well developed foehn nose over the South Island highlighting the pressure field deformation caused in the gradient north-westerly airstream by the Southern Alps. Hourly trans-alpine (Hokitika – Christchurch) surface level atmospheric pressure differences throughout this event indicate that substantial upwind blocking and lee trough development did

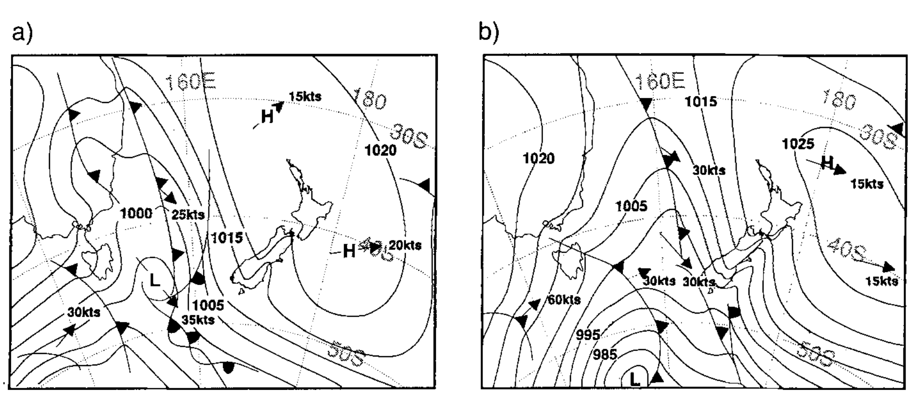
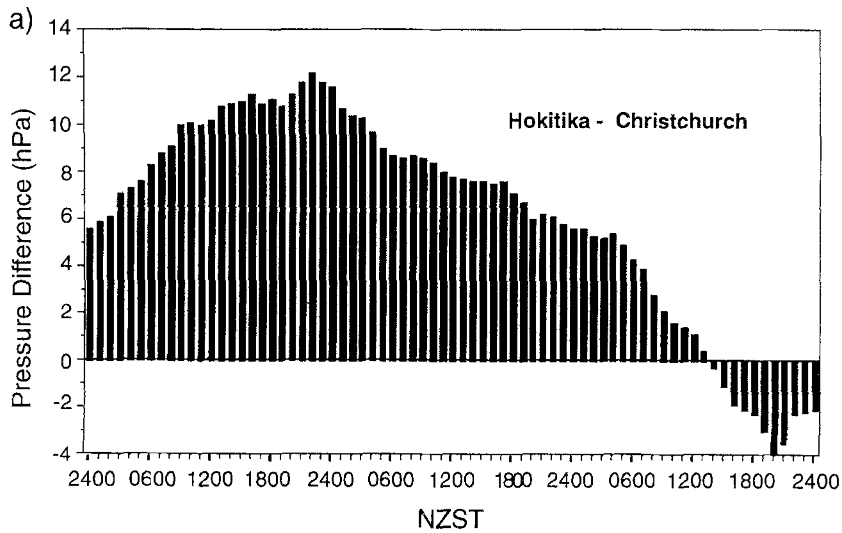


Fig. 3. Mean sea level synoptic analyses for (a) 1200 NZST 18th October 1992, (b) 1200 NZST 19th October 1992



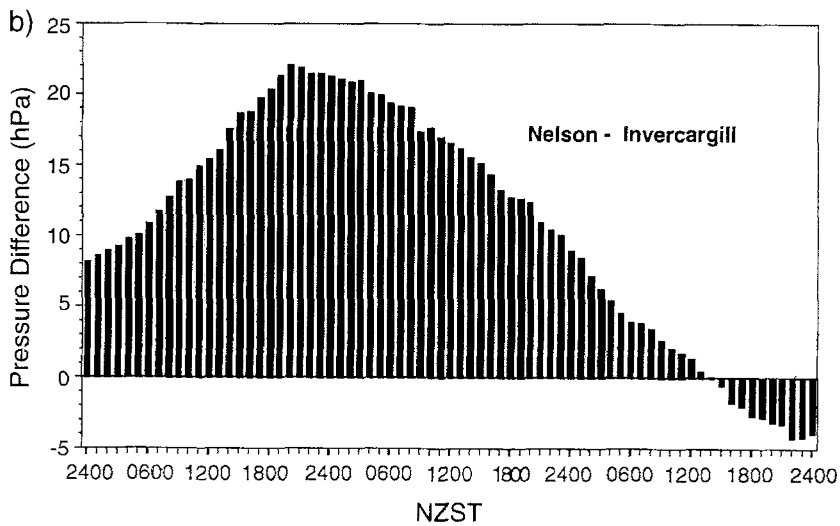


Fig. 4. Regional sea surface atmospheric pressure gradients for the 18th to 20th October 1992 for (a) Hokitika-Christchurch, (b) Nelson-Invercargill

occur (Fig. 4a). The strength of the gradient airflow over the South Island is perhaps best expressed by the pressure difference between Nelson and Invercargill (Fig. 1) which for this event is shown in Fig. 4b. This indicates that the northeast – southwest pressure gradient over the South Island intensified throughout the 18th October to reach a maximum of approximately 1 hPa per 30 km at 2000 NZST on the 18th October 1992. The regional pressure gradient them gradually weakened before reversing at 1400 NZST on the 20th October 1992 (Fig. 4b).

Regional airflow characteristics over the lower North Island and the South Island during this event are mapped in Fig. 5. At 1200 NZST on the 18th October 1992 airflow was light and variable over most of southern New Zealand with local effects dominating (Fig. 5a). However, wind speed and direction observations from southwestern sites indicate the presence of light to moderate north-westerly airflow at this time. Twelve hours later at 2400 NZST, northwesterly conditions were recorded at the majority of sites (Fig. 5b). Two distinctive features of the regional windfield at this time were that the near surface airflow along the west coast of the South Island was flowing as a northeasterly, almost parallel to the Southern Alps, indicating that blocking of low level onshore airflow was occurring. Secondly, airflow was being topographically channelled through Cook Strait to veer onshore at Christchurch and Kaikoura (Fig. 5b). Northeasterly airflow along the east coast of the South Island during such synoptic conditions is indicative of the Canterbury Coast lee trough northeasterly as discussed by McKendry et al. (1986). Similar regional airflow patterns are identifiable in several similar diagrams presented by Sturman (1992) in his discussion of south-

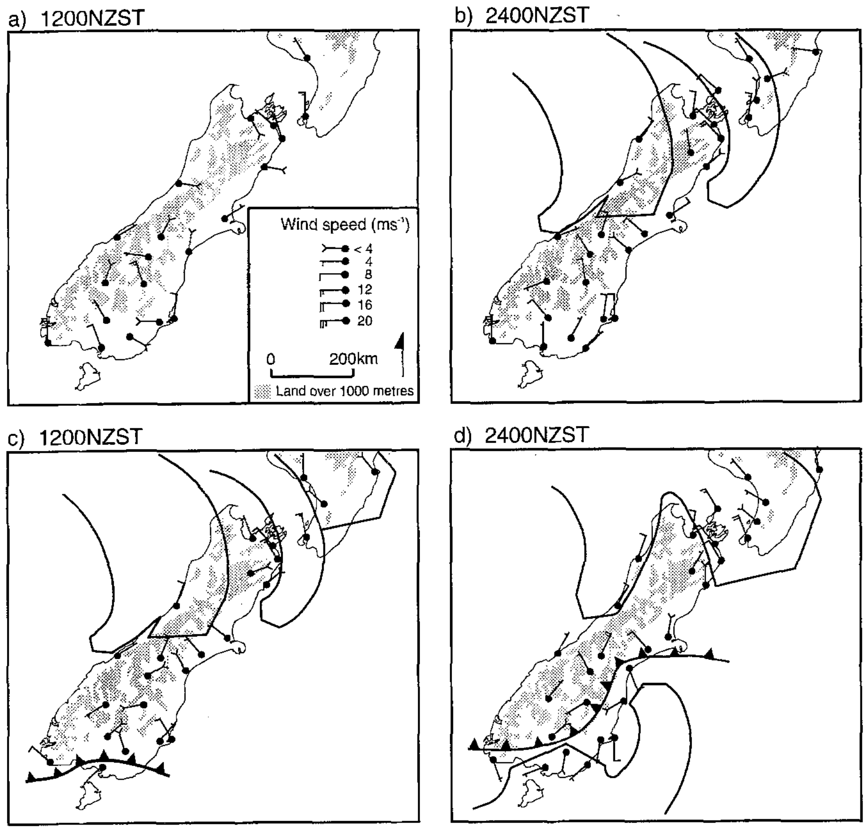


Fig. 5. Regional surface windfield maps for (a) 1200 NZST 18th October 1992, (b) 2400 NZST 18th October 1992, (c) 1200 NZST 19th October 1992, (d) 2400 NZST 19th October 1992

erly changes over the South Island made during SOUCHEX (Southerly Change Experiment).

The regional windfield changed little over the following 12 hours as seen by the airflow characteristics presented in Fig. 5c, although some wind directions appear more variable and a southwesterly change is apparent at Invercargill. By 2400 NZST, the southerly change had advanced further north along the east coast of the South Island apparently in the lee of the Southern Alps, while northwesterly winds prevailed over the remainder of southern New Zealand (Fig. 5d). A reversal of the Nelson-Invercargill and the trans-Alpine pressure gradient (Fig. 4) identify the cessation of this foehn event at approximately 1300 NZST on the 20th October 1992 as southwesterly gradient airflow became dominant over the South Island.

Vertical profiles of wind speed and direction obtained from soundings conducted at Hokitika Airport during this event (Fig. 6) confirm that blocking did occur over the West Coast, which resulted in the formation a barrier jet below approximately 1800 m. Airflow above 1800 m veered throughout the event from the southwest to the northwest as wind speeds increased. The barrier jet is indicated by the quite strong north to northeast flow which started near the surface at

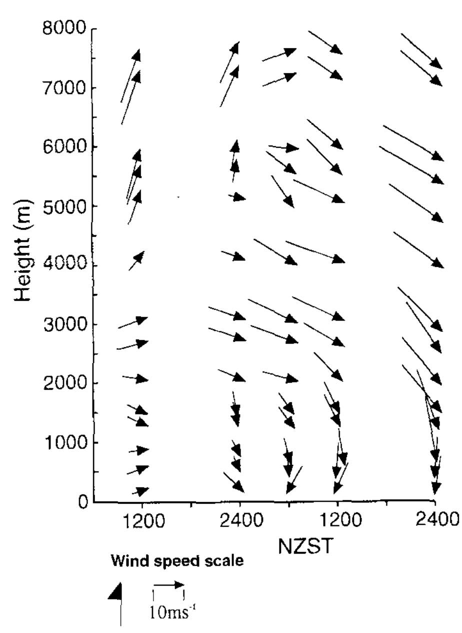


Fig. 6. Vertical wind speed and direction profiles from Hokitika Airport for the 18th and 19th October 1992

0600 NZST on the 19th October. Although theoretically predicted, barrier jet formation along the west coast of the South Island has not previously been documented. The development of a barrier jet has considerable theoretical and applied implications with respect to foehn theory and forecasting. For example, it has usually been assumed that surface level airflow during similar synoptic conditions, to those presented in Fig. 3 is forced over the Southern Alps, rather than around them. This hypothesis appears to have been based on the assumption that onshore northwesterly airflow of subtropical origin, was unstable by nature and would therefore offer least resistance to its forced ascent by the mountain barrier. Consequently, the onshore airflow was assumed to rise approximately 2500 m before descending east of the alpine divide, where warming by adiabatic compression and the release of latent heat due to condensation upwind of the Southern Alps, was significantly greater than cooling associated with the evaporation of precipitation spillover. However, due to barrier jet formation and upwind blocking, air reaching the ground east of the Southern Alps may have originated from a level of 1500 to 1800 m in the west. It may therefore only need to rise a few hundred metres to ascend the Southern Alps and theoretically should initially contain less moisture than if the air originated from lower levels. It therefore seems fair to suggest that the importance of latent heat released by the forced ascent of air during this type of event is considerably less than previously thought. Secondly, barrier jet formation has important implications with respect to orographic rainfall enhancement and precipitation patterns along the west coast of the South Island. During these conditions, a distinctly different orographic regime is likely to influence and determine precipitation enhancement along the West Coast, rather than if onshore airflow was normal to the coastline and the Southern Alps at low levels.

5.2 Conditions at Lake Tekapo

Meteorological observations made by three automatic weather stations located at sites 1, 2 and 3 (Fig. 2) in the Lake Tekapo area immediately east of the Southern Alps on the 18th and 19th October 1992 are presented in Fig. 7. Unusually warm nocturnal air temperatures and low relative humidities were recorded at sites 1 and 2 at 0100 NZST on the 18th October 1992, indicating the presence of foehn conditions. Relatively little change was recorded by the weather station at site 1 until the onset of daytime heating at approximately 0800 NZST, when the usual increase in air temperature and decrease in relative humidity occurred (Fig. 7a) . However, further south at site 2, a marked decrease in air temperature, higher relative humidities and variable winds suggest a decoupling of the foehn airstream from the surface at approximately 0200 NZST, which allowed the onset of localised cold air drainage. Local thermotopographic circulations were recorded over the southern margins of the study area at site 3 until 1700 NZST on the 18th October 1992, when the onset of the northerly foehn was recorded. This was approximately six hours after onset at site 2 and reflects the ability of the local extended lake breeze circulation system to remain decoupled from the developing foehn airstream (McGowan et al., 1995) within the lake basin. Comparatively clear skies over the study area on the 18th October undoubtedly enhanced the development of such local thermal circulations by allowing almost maximum surface heating to occur for the time of year.

Displacement of the foehn wall east of the alpine divide on the 19th October, resulted in extensive cloud cover over the Lake Tekapo study area and eventually rainfall. As a result, the strong thermal daytime temperature modulation present on the 18th October was absent from each station's record on the 19th October (Fig. 7). Instead, the temperature and relative humidity records indicate little change from approximately 2000 NZST on the 18th October until the onset of rainfall on the 19th October 1992 (Fig. 7). Rain (spillover) was first recorded at site 1 at 1000 NZST on the 19th and increased in intensity throughout the day (Fig. 7a). Undoubtedly increased upper level wind speeds as indicated by the soundings from Hokitika Airport (Fig. 6) throughout the 19th October enhanced the spillover process. At 1900 NZST, light rain was recorded at site 2 (Fig. 7b), with only a trace reported from site 3. Over the western slopes of the Southern Alps rain fell throughout the 19th October 1992 with 164 mm recorded at Fox Glacier township (Fig. 1). This was approximately four times the rainfall recorded in the upper Godley Rever Valley at site 1, only 40 km

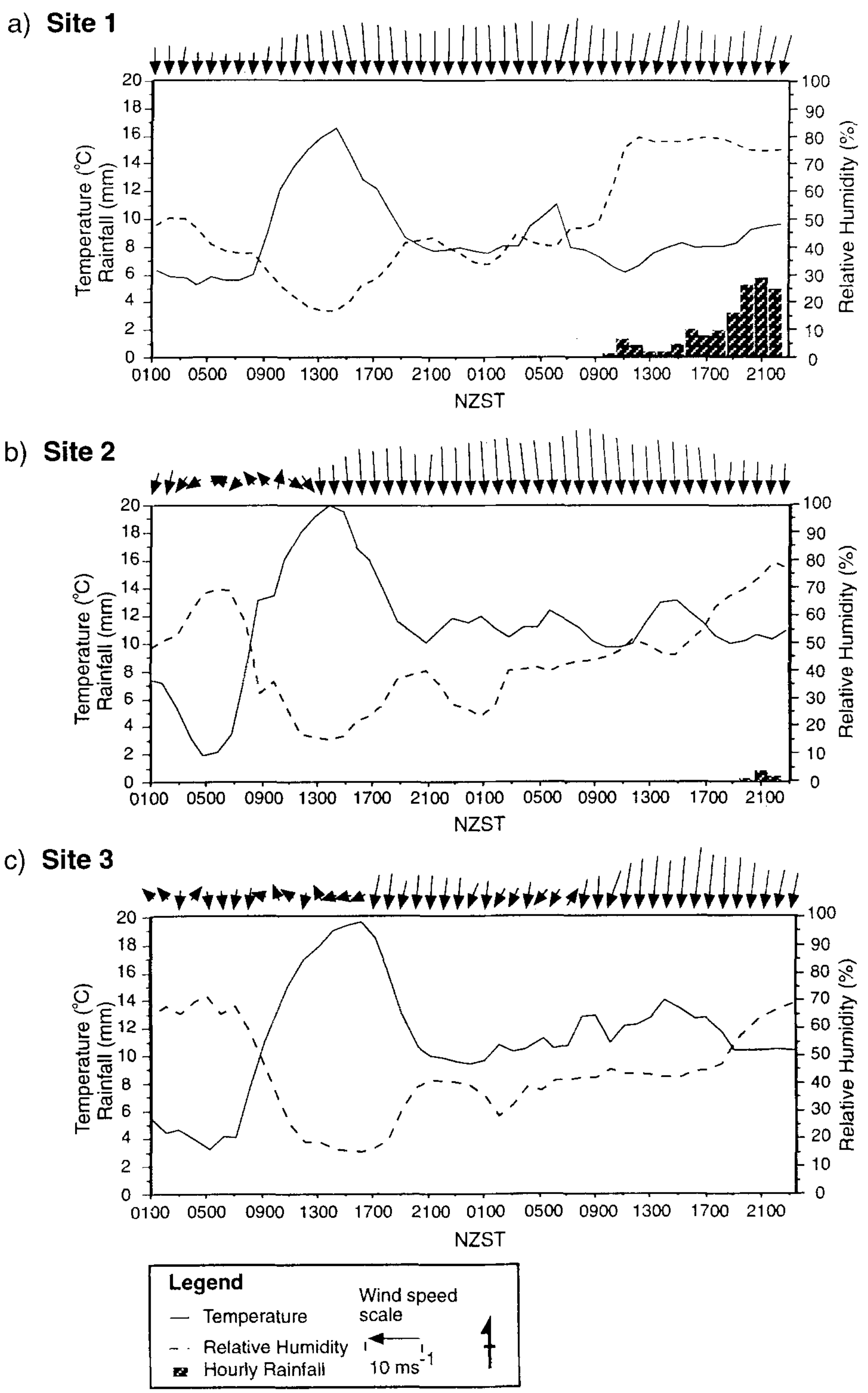


Fig. 7. Meteorological observations from the Lake Tekapo study area for the 18th and 19th October 1992

to the east and highlights the strong precipitation gradient that exists across the Southern Alps during foehn conditions. Cessation of this foehn event occurred around mid-day on the 20th October 1992 as a cold front travelled across the South Island ahead of weak southerly airflow. This produced a reversal in the trans-alpine and Nelson-Invercargill pressure gradients as displayed in Fig. 4.

This typical spring-time foehn event was notable for initiating the most severe dust storm to affect Tekapo Village (Fig. 2) in recent years which caused nuisance to residents and visitors alike. Similar events were reported throughout the spring of 1989 which were linked to health problems amongst local residents and were considered to seriously threaten the local tourism industry. Rainfall during foehn wind storms effectively arrests all dust storm activity, while providing valuable inflows into Lake Tekapo. Precipitation and snow and ice melt throughout this northwesterly event increased the inflows into Lake Tekapo by almost 850%, raising the lake level by approximately 1.14 m. This significantly increased the generation potential of this hydroelectric reservoir, while providing substantial flow-on effects to down stream power stations.

6. Event 2: 10th and 11th January 1993

6.1 Synoptic and Regional Windfields

The second type of foehn event to be observed over southern New Zealand is associated with disturbed west to southwesterly gradient airflow. Typically, several frontal systems may be embedded within the sub-polar airstream, which on encountering the upwind effect of the Southern Alps regularly veers to become more westerly in direction. Between the frontal systems ridging usually occurs, which results in short periods of west to northwesterly airflow over the South Island before the synoptic airstream backs to the southwest. Such conditions may result in heavy snowfalls along the Southern Alps during winter, and produce "cold" foehn conditions over eastern South Island districts.

Figure 8 presents a series of surface level synoptic analyses for the 10th and 11th January 1993. A light synoptic northwesterly airflow extended over New Zealand throughout the morning of the 10th January ahead of an approaching cold front (Fig. 8a,b). Near surface wind speed and direction observations for both 0600 NZST and 1200 NZST on the 10th January show that airflow was topographically channelled around the South Island flowing through both Cook and Foveaux Straits (Fig. 9a,b). By 1800 NZST, nearly all surface level monitoring sites recorded west to north westerly airflow (Fig. 9c). A lee trough was also well developed over the eastern South Island on the 10th with mean hourly air pressure at Hokitika approximately 11 hPa higher than Christchurch (Fig. 10a)

Between 1800 NZST on the 10th and 0700 NZST on the 11th January the first cold front crossed the South Island. This had little effect on the trans-alpine pressure gradient as ridging ahead of a second front meant that airflow along the west coast of the South Island remained onshore (Fig. 9f). Vertical wind speed and direction profiles from Hokitika Airport during this event show that airflow throughout the 7200 m profile remained westerly throughout the event (Fig. 11). No barrier

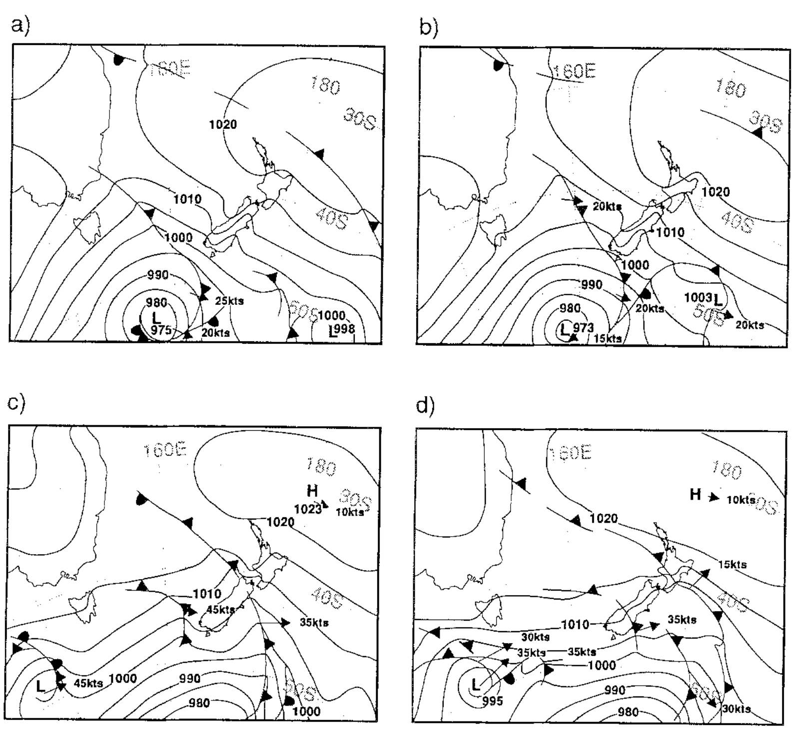


Fig. 8. Mean sea level synoptic analyses for (a) 0600 NZST 10th January 1993, (b) 1200 NZST 10th January 1993, (c) 0600 NZST 11th January 1993, (d) 1200 NZST 11th January 1993

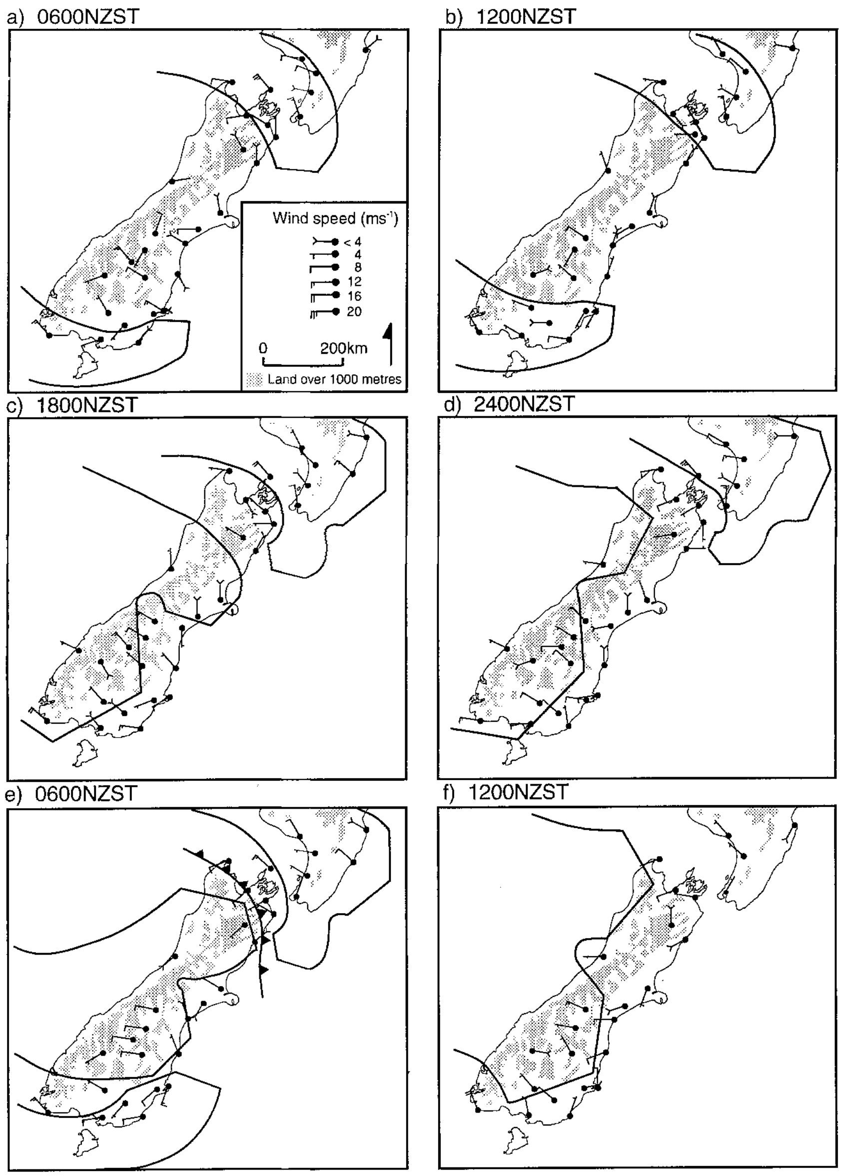


Fig. 9. Regional surface windfield maps for (a) 0600 NZST 10th January 1993, (b) 1200 NZST 10th January 1993, (c) 1800 NZST 10th January 1993, (d) 2400 NZST 10th January 1993, (e) 0600 NZST 11th January 1993, (f) 1200 NZST 11th January 1993

jet was observed to develop, thereby suggesting that the onshore airflow was able to ascend the Southern Alps. Lower wind speeds below approximately 1800 m during this event were associated with a gradient airflow almost perpendicular to the mountain barrier, and this may account for the absence of a barrier jet.

6.2 *Conditions at Lake Tekapo*

Typical foehn conditions such as warm ambient air temperatures, low relative humidities and variable winds were recorded by the three weather stations located within the Lake Tekapo study area. Intermittent rainfall was monitored throughout the 10th January 1993 at site 1 in the upper Godley River Valley due to wind drift of precipitation over the mountains (Fig. 12a). By 1900 NZST, the foehn wall had moved east of the alpine divide resulting in rainfall over the entire lake basin. Five hours later at 0100 NZST on the 11th January 1993, the wind backed through approximately 35° over the southern margins of the lake basin to originate from the west-northwest (Fig. 12c), while topographic channelling of the gradient airstream resulted in a continuation of northerly airflow at sites 1 and 2. The wind shift may well have been associated with the passage of the cold front at this time over the central South Island.

A small ridge developed over the South Island

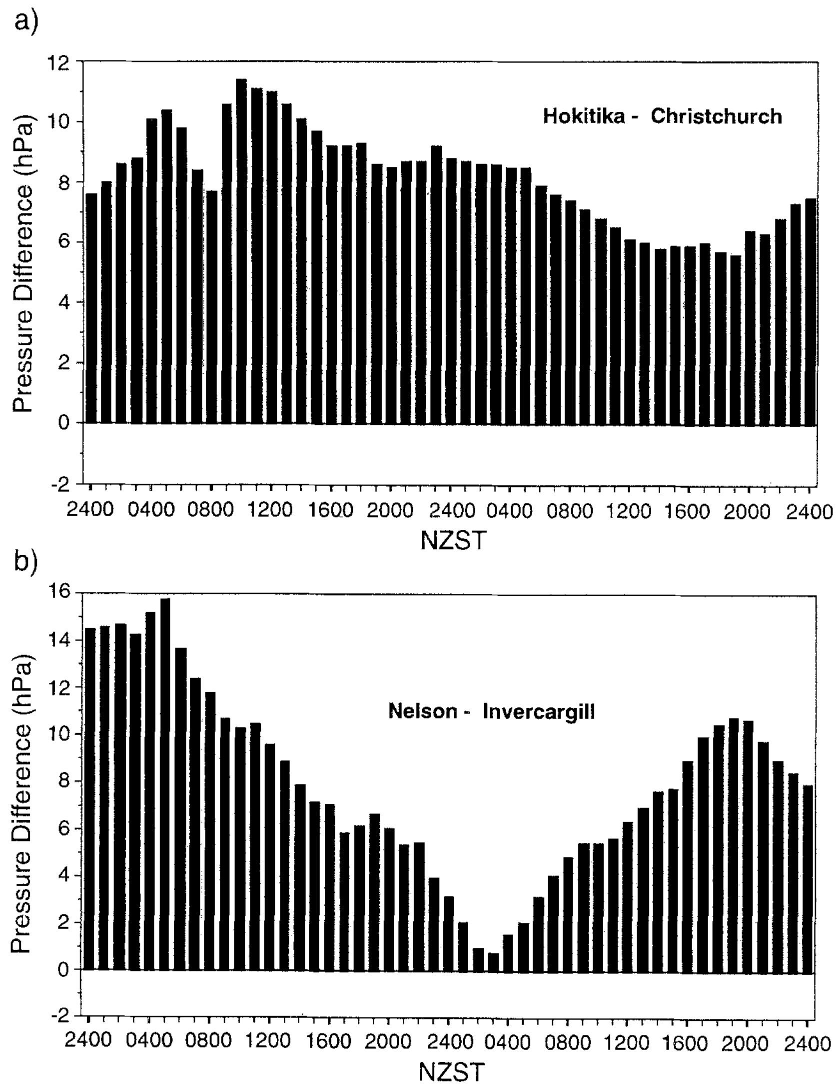


Fig. 10. Regional sea surface atmospheric pressure gradients for the 10th to 11th January 1993 for (a) Hokitika-Christchurch, (b) Nelson-Invercargill

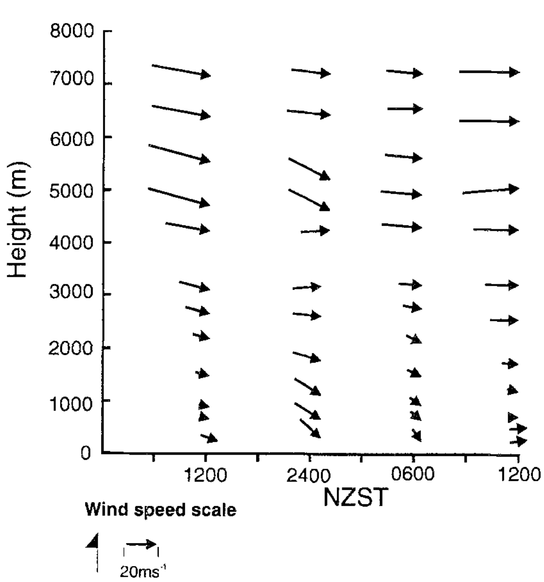


Fig. 11. Vertical wind speed and direction profiles from Hokitika Airport for the 10th and 11th January 1993

as seen in the 0600 NZST synoptic analysis (Fig. 8c) ahead of a second cold front, which was embedded within the gradient westerly airstream. This produced surface level southwesterly airflow over the northwest of the South Island, while channelling through both Cook and Foveaux Straits continued with airflow converging into the lee trough along the eastern South Island (Fig. 9e). Inland sites observed moderate westerly winds at this time. Six hours later as the second front moved over the South Island, surface level airflow backed to the northwest over the southern coast, while most other stations recorded west to southwesterly winds. This sequence of small cold fronts embedded within a disturbed westerly airstream continued to affect southern New Zealand until the 24th January 1993, after which more settled summer-time anticyclonic conditions prevailed.

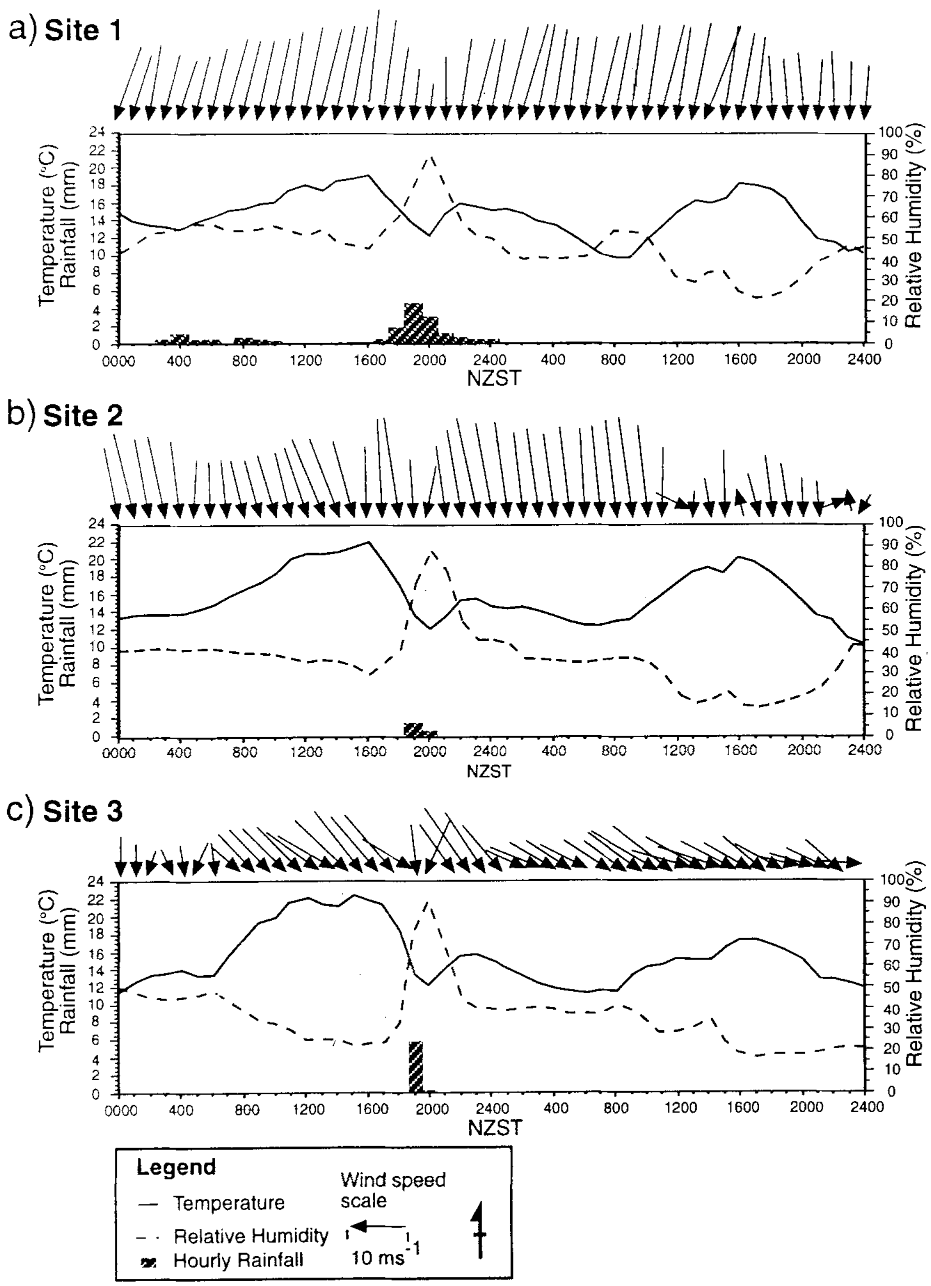


Fig. 12. Meteorological observations from the Lake Tekapo study area for the 10th and 11th January 1993

7. Summary and Conclusion

Two case studies have been presented to examine the development of foehn conditions over southern New Zealand during two different synoptic situations and to relate synoptic and regional windfields to conditions within one of the major alpine lake basins. Dynamic modification of synoptic west to northwesterly airflow by the Southern Alps typically culminates in classic foehn conditions over eastern South Island districts, while west of the divide orographic rainfall usually occurs. During the more northerly gradient wind event blocking of the onshore airstream was observed below 1500 to 1800 m over the west coast. This appears to result in the development of a barrier jet and the channelling of airflow around the South Island through both Foveaux and Cook Straits. Analysis of wind speed and direction observations from South Island monitoring sites identified this airflow to then spiral into a lee trough along the east coast. During disturbed west-southwesterly synoptic conditions, the Southern Alps may cause the gradient airstream to veer so that it becomes more westerly in direction before flowing onshore. Under these conditions barrier jet develop was not observed thereby suggesting that the airstream was more likely to ascend the Southern Alps.

In both situations, observations from automatic weather stations made in the immediate lee of the alpine divide, in the Lake Tekapo catchment, indicate that the onset of foehn conditions occurs first in the headwaters of the large alpine river valleys. Onset at this site may precede that at another only a few kilometres down valley by 12 hours or more. At this second site, local thermo-topographic circulations such as the extended lake breeze may dominate. As the trans-alpine gradient flow intensifies ahead of the approaching frontal system and associated trough, displacement of the foehn wall east of the alpine divide usually occurs. This regularly results in spillover into the eastern alpine catchments such as Lake Tekapo. The heaviest falls appear to be associated with the passage of the front over the monitoring sites. Topographic channelling of the trans-alpine air-stream down the large deeply incised river valleys such as the Godley and Macaulay River Valleys enhance local wind speeds and result in localised jetting within the valley systems. As a result, extremely high wind speeds were recorded within the Godley River Valley during such events, which at times exceeded 50 to 60 ms^{-1}. These observations support earlier documented accounts of such extreme wind speeds within the Southern Alps during foehn windstorms, as discussed by Chinn (1980), McCracken (1980) and Allan (1991).

Observations made by this study have important practical and theoretical implications regarding forecasting, rainfall distribution and orographic rainfall enhancement over the west coast of the South Island, and meso-scale modelling of atmospheric processes over the Southern Alps. Clearly, many questions about foehn development over the South Island still need to be addressed. The conditions leading to barrier jet formation and their influence on rainfall distribution and development, linkages between spillover and different synoptic conditions and the evolution of foehn windstorms over the eastern South Island. Hopefully the current SALPEX experiment programme will address these issues regarding arguably the most dominant feature of southern New Zealand's weather and climate.

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References

Allan, J. C., 1991: Storm induced surf zone processes and beach profile response at Lake Pukaki, South Island, New Zealand. Unpublished MSc Thesis, University of Canterbury, Christchurch, New Zealand, 212 pp.

Atkinson, B. W., 1981: *Mesoscale Atmospheric Circulations.* London: Academic Press, 495 pp.

Bowen, A. J., 1981: Engineering aspects of the wind. *Weath. and Clim.*, **1**, 14–20.

Brinkmann, W. A. R., 1971: What is a foehn? *Weather*, **26**, 230–239.

Chinn, T. J., 1980: Sundry wind records from the Southern Alps. Report No WS163, National Water and Soil Conservation Organisation, Christchurch, New Zealand, 14 pp.

Garr, G. E., Fitzharris, B. B., 1991: A climate classification of New Zealand based on numerical techniques. *NZ. Geographer*, **47**, 60–71.

Hann, J., 1866: Zur Frage über den Ursprung des Föhns. *Zeit. Oest. Gesell. Meteor.*, **1**, 257–263.

Hoinka, K. P., 1985: Observation of airflow over the Alps during a foehn event. *Quart. J. Roy. Meteor. Soc.*, **111**, 199–224.

Justice, J. A., 1990: Hydro Resources of New Zealand, Resource Information Report 7, Energy Resources Division, Ministry of Commerce, Wellington, New Zealand, 57 pp.

Kidson, E., 1932: The Canterbury "Northwester". *NZ. J. Sci. Tech.*, **14**, 65–75.

Lamb, P. C., 1972: An Investigation of the Canterbury nor-Wester. Unpublished MA. Thesis, University of Canterbury, Christchurch, New Zealand, 175 pp.

Lamb, P. C., 1975: The Nor'wester's advance across the Canterbury Plains, New Zealand. *NZ. J. Sci.*, **17**, 375–379.

Lisle, J. F. de, 1969: The climate and weather. In: Knox, G. A. (ed.) *The Natural History of Canterbury*. Wellington, New Zealand: Reed.

McCracken, I. J., 1980: Mountain climate in the Craigieburn Range, New Zealand. In: Beneke, U., Davies, M.R. (eds) *Mountain Environments and Subalpine Tree Growth.* Wellington, New Zealand: New Zealand Forest Service, 41–59.

McGowan, H. A., 1994: Thermal and dynamic influences on alpine dust storms, Lake Tekapo, New Zealand. Unpublished Ph.D Thesis, University of Canterbury, Christchurch, New Zealand, 268 pp.

McGowan, H. A., Owens, I. F., Sturman, A. P., 1995: Thermal and dynamic characteristics of alpine lake breezes, Lake Tekapo, New Zealand, *Bound.-Layer Meteorol.* (in press).

McKendry, I. G., Sturman, A. P., Owens, I. F., 1986: A study of interacting multiscale wind systems, Canterbury Plains, New Zealand. *Meteorol. Atmos. Phys.*, **35**, 242–252.

Oke, T. R., 1987: *Boundary Layer Climates*, 2nd edn. London: Routledge, 435 pp.

Orlanski, I., 1975: A rational subdivision of scales for atmospheric processes. *Bull. Amer. Meteor. Soc.*, **56**, 527–530.

Ryan, A. P., 1987: The Climate and Weather of Canterbury. Miscellaneous Publication 115(17). Wellington, New Zealand: New Zealand Meteorological Service, 66 pp.

Sturman, A. P., 1992: Dynamic and thermal effects of surface airflow associated with southerly changes over the South Island, New Zealand, *Meteorol. Atmos. Phys.*, **47**, 229–236.

Wratt, D. S., Ridley, R. N., Sinclair, M.R., Larsen, H., Henderson, R., Austin, A. A., Sturman, A. P., Owens, I. F., Fitzharris, B. B., Ryan, B. F., 1995: The New Zealand Southern Alps experiment. (submitted for publication).

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