Southerly Changes on the East Coast of New Zealand

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(Manuscript received 3 April 1990, in final form 2 November 1990)

ABSTRACT

A combined observational and climatological study of orographically influenced cold fronts over New Zealand, known locally as "southerly changes," is presented.

Four southerly changes that occurred along the east coast of New Zealand during the Southerly Change Experiment (SOUCHEX) in January and February of 1988 are analyzed in detail using the higher spatial and temporal density of data established for the experimental period. Three of the southerly changes were associated with fronts originating over the Tasman Sea, while the other was not.

A common feature in all four cases was the shallowness of the southerly flow for some hours after the surface wind change. The top of the southerly flow layer was less than the typical height of the Southern Alps (2000 m). Above this there was usually a maximum of the northerly component of the flow at or just above mountain-top levels and in three cases the prefrontal low-level flow was dominated by a warm northwesterly foehn. In the central South Island the northwards motion of the southerly change line at the surface was more rapid on the coast than inland. In this and other respects, the changes had many of the characteristics of "southerly busters" in southeastern Australia, and it seems likely that the dynamical mechanisms of both kinds of fronts are similar.

1. Introduction

New Zealand is a long and narrow country extending from approximately 34° to 47°S. Most of the land area of approximately 250 000 km^2 is contained in the two major mountainous islands. The North Island has its ranges, with many peaks over 1500 m, some 60 km inland from the east coast between East Cape and Cook Strait. The South Island mountains are higher, with many peaks over 2500 m. In the central part of the South Island the main range, the Southern Alps, is within 40 km of the west coast with the Canterbury Plains to the east, but farther north and south a series of mountain ranges extends across almost the entire breadth of the island. Places named in the text are shown in Fig. 1 and the terrain above 1000 m is shaded.

New Zealand lies in the zone of disturbed westerly flow at upper levels. In the longitude of New Zealand, the analyses of Crutcher et al. (1971) reveal that in the mean flow there is a jet stream with its core at about 27°S and at the 200-hPa level in all seasons except summer. In winter and spring there is a second jet stream at about 60°S with its core at 100 hPa or above, but with the secondary maximum wind speeds evident down to middle-tropospheric levels. In summer the mean winds are generally lighter; there is a broad area of upper tropospheric winds exceeding 20 m s^{-1} between about 25° and 60°S. At times there are only small perturbations in the westerlies, but in other periods there are significant meridional components to the flow. Major development of synoptic-scale weather systems is often associated with such perturbations of the westerlies (e.g., Hill 1969, 1980).

Coulter (1975) has reported on the weather patterns over New Zealand as depicted on mean sea level charts. They show commonly a succession of eastward migrating anticyclones, typically some 1000 km from west to east, passing over at 3–7 day intervals. The troughs

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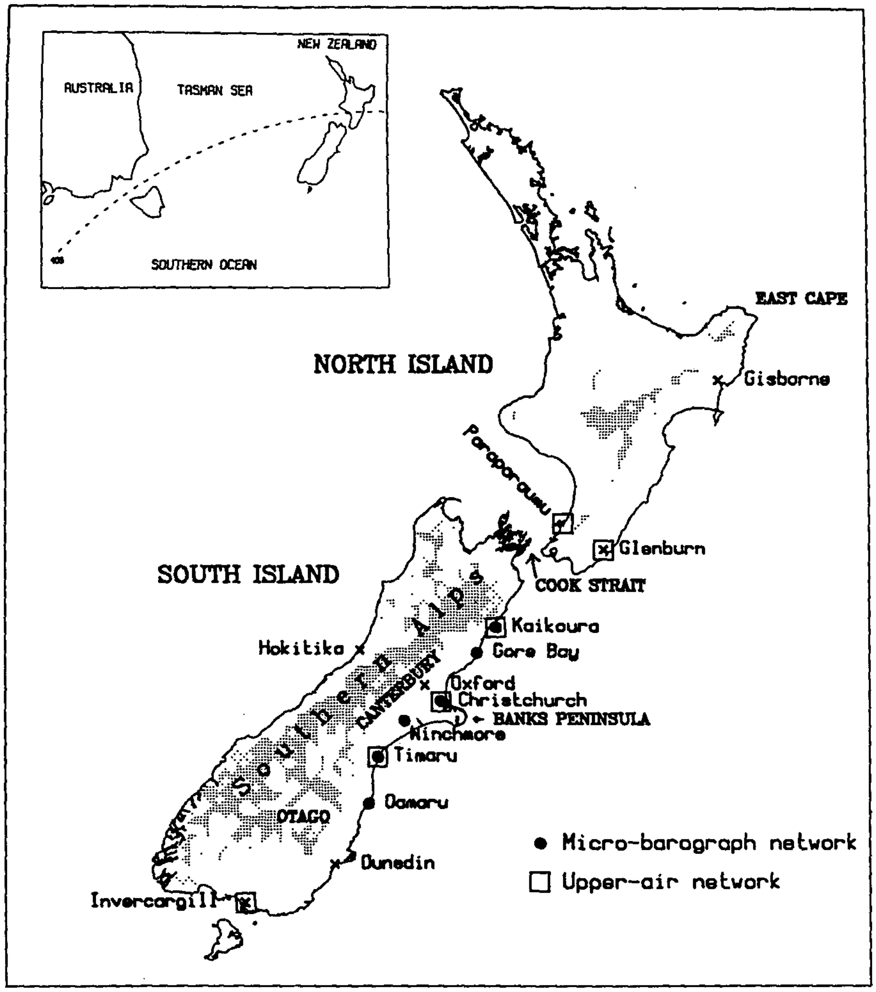

FIG. 1. Maps of New Zealand and surroundings with place names mentioned in the text. The microbarograph network (filled circles) and the upper-air network (squares) are shown also.

between the anticyclones usually contain one or more cold fronts oriented meridionally or northwest–southeast. Their passage is preceded by northerly winds and increasing cloud and rain in areas where the wind is onshore. The fronts are followed by winds between west and south with showery weather accompanying the postfrontal airflow where the flow is onshore. Because of the orientation of the main New Zealand ranges this may be on either the west or the east coast; only a small shift in the gradient flow direction causes a dramatic change in the distribution of showers.

The mountain ranges cause major distortions of the wind flow and pressure pattern. Hutchings (1944) demonstrated the establishment of a ridge on the windward side of the mountains with a trough on the lee side in northwesterly conditions. As shown by de Lisle (1965), very strong winds are most frequent in the far north of the North Island in and about Cook Strait between the main islands and about the south coast of the South Island, reflecting a tendency for the winds to blow around these mountainous islands or through the only major break in the mountain chain. The effect of Cook Strait is discussed by Stainer (1983). There is also a component of the flow over the mountains, which in west to northwest airflows give rise to air with a high potential temperature descending on the lee side (Ryan 1987) and may cause some mountain wave activity (Farkas 1958; Cherry 1972). These airflow patterns have been discussed by Smith (1982) and simulated numerically by Ulrich (personal communication).

Sea breezes are common in New Zealand in the warmer months. On the east coast of the South Island there are complex wind flows particularly when the gradient flow is from the westerly quarter. There may be warm surface winds from the northwest, a true sea breeze, or a northeasterly wind, which is very common north of Banks Peninsula and is caused at least partly by forcing of the flow through Cook Strait (as shown by the calculations of Ulrich and Smith). Trenberth

(1977) shows that the orographic trough over the inland areas of the eastern South Island is enhanced in the afternoon by local heating giving rise to a horizontal mesoscale circulation. Further aspects of the wind regime in the east of the South Island are discussed by McGann (1983), McKendry (1983), McKendry et al. (1986), and Ryan (1987), who examine the spatial, annual, and diurnal variability of the wind field. Similar orographic and heating effects are known to occur on the east coast of the North Island, but they have not been subject to systematic studies.

When a northwest flow is established and there is a subsequent southerly or southwesterly change, there is often a very rapid fall in temperature. Crawford (1977) and Revell et al. (1987) document a case when the temperature at Christchurch fell by 20°C, the synoptic situation for which is shown in Fig. 2. The pattern shown is typical of such events; the surface front becomes distorted as it crosses the South Island, and the change on the east coast advances into an orographic trough associated with the prefrontal cross-mountain flow. Note also the lack of data generally available for

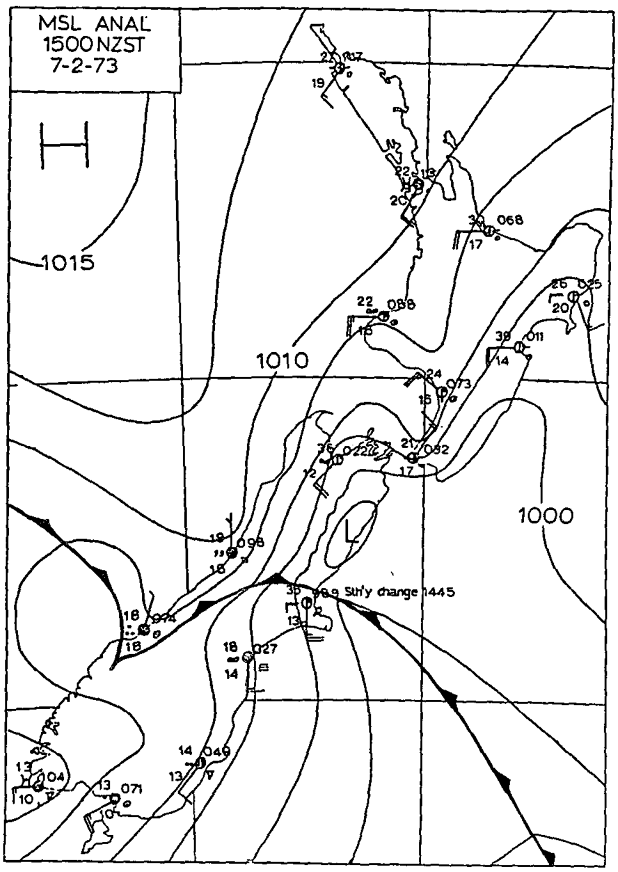

FIG. 2. New Zealand Meteorological Service mean sea-level pressure analysis for 1500 NZST (1600 NZDT) on 7 February 1973, from Crawford (1977).

positioning the front off the coast. Southerly changes may be associated with a synoptic-scale front identified in satellite imagery over the Tasman Sea, or they may be generated locally. Revell et al. (1987) analyzed the northward progression and vertical structure of 10 southerly changes at all times of the year using the hourly observations from east coast stations, the 12-h radiosonde soundings at Christchurch and the 6-h upper-level winds at Christchurch. The changes were of various types. In three cases the southerly flow did not extend above 700 hPa. They noted also that high temperatures ahead of the change often led to squally changes and that the surface cold front as defined from discontinuities in the wind, pressure, and temperature fields often became separated from the parent cloud system. Earlier Hill (1969) undertook a case study of a wintertime southwesterly regime over New Zealand using the routine synoptic and upper-air data. As radiosonde data were available only at 24-h intervals his results are necessarily subjective. He located frontal discontinuities in time sections, but they were not all identifiable at the surface, particularly the warm fronts.

In New Zealand, as in other parts of the world, there has been a remarkable improvement in ability to forecast synoptic-scale weather systems. Gordon (1984) shows that the skill in 72-h forecasting in the New Zealand area of the European Centre for Medium Range Weather Forecasting (ECMWF) model is comparable to that for 24-h before the prognoses from ECMWF were available. However, some significant weather changes are not adequately predicted by current models. The southerly change on the east coast is one such feature. The Southerly Change Experiment (SOUCHEX) was planned, therefore, to study the structure and evolution of these changes on the east coast of New Zealand, their inland penetration, and the role of the lee trough on the development of such changes (Steiner et al. 1987). Although the experimental area covered the entire east coast of New Zealand from Invercargill to East Cape, particular attention was given to the Canterbury Plains where changes often reach their peak intensity.

Another objective of the present study was to compare the structure and evolution of southerly changes on the east coast of New Zealand with those in eastern Australia, which have been studied in detail by Colquhoun et al. (1985) and Coulman et al. (1985).

A preliminary step in planning the experiment was to perform a climatological study of southerly changes (Ridley 1987). Results of this are summarized in section 2. The SOUCHEX itself was carried out between 14 January and 12 February 1988 as a collaborative project between the New Zealand Meteorological Service, the Geophysical Fluid Dynamics Laboratory of Monash University in Melbourne, and the Geography Department of the University of Canterbury. The conventional data network operated by the New Zealand Meteorological Service was supplemented by:

(i) additional rawin- and radiosonde soundings from the regular observing stations at Invercargill, Christchurch, and Paraparaumu and from two Vaisala omegasonde stations installed at Timaru and on a ship off Banks Peninsula,

(ii) airsonde soundings of wind and temperature at Kaikoura and Glenburn,

(iii) pilot balloon wind soundings from Christchurch and Oxford to the west of Christchurch on the Canterbury Plains,

(iv) Doppler acoustic sounder determinations of low-level winds (up to 900 m) at Winchmore on the Canterbury Plains,

(v) additional surface observations (during special observational periods the automatic weather stations on the east coast were interrogated at quarter-hour intervals and additional surface instruments including a network of microbarometers were deployed in the central South Island),

(vi) aircraft data (an F-27 aircraft instrumented by the New Zealand Meteorological Service was available for the final event and was used to make low-level passes through the southerly change, providing frontal locations over the sea), and

(vii) satellite data (data from NOAA orbiting satellites and from GMS, obtained at 3-h intervals at low resolution, were archived for all events studied).

Five southerly changes were studied, the first on 14 January being one of the strongest of its type. Event 4 (on 27–28 January), although expected to develop, did not advance beyond Dunedin and was not documented in any detail. The other four formed in dissimilar synoptic situations, although these situations were considered typical of those that commonly produce such changes. Indeed, we considered ourselves fortunate to be able to document such a range of situations. As a result, however, we have not been able to construct a single composite model for changes, and our description of synoptic aspects in section 3 and vertical structure in section 4 are separate for each event. However, common features are drawn together in the discussion in section 6. Mesoscale aspects and isochronology are discussed in section 5 and more comprehensively by Sturman et al. (1990). Due to the intense nature of event 1 and the range of phenomena associated with it, we discuss this event at greater length than the other events.

2. Climatology

Ridley (1987) prepared a climatology of southerly changes at Christchurch, making use of hourly reports over a 7-yr period from January 1980 to December 1986, inclusive. Christchurch was selected because of the availability of reports covering the full 24 h. It is an appropriate location because of its proximity to the area where many southerly changes are very pronounced, and because its wind regime is composed of clearly defined preferred directions making identification of southerly changes relatively easy.

A total of 559 southerly change events were found where an event required the mean (10-min) southerly wind speed to exceed 5 m s^{-1} for two consecutive hourly reports, or to exceed 8 m s^{-1} for any single hourly report. These events were then categorized according to the nature of the wind change, the strength of the ensuing southerly wind, and the magnitude of the associated temperature drop. "Significant" events were those for which the maximum mean southerly wind strength occurred within 3 h of the change and exceeded 8 m s^{-1}. Thus *significant* events are those that pose a difficult forecasting problem in terms of their abrupt nature and strength. Of the total number of events, 195 (or 35%) fell into this category, i.e., about 28 each year on average. *Temperature* events are those southerly changes accompanied by a marked temperature drop (see Ridley 1987 for a full definition). Temperature events accounted for only 22% of the total, however they accounted for almost half of the significant events.

Just under half ($\sim$13 each year) of the significant events had a mean southerly wind speed in excess of 11 m s^{-1}. These represent the southerly buster type change as observed along the New South Wales coast of Australia (see, e.g., Colquhoun et al. 1985) and described in the New Zealand context by Ridley (1990). The above figures are similar to those of Colquhoun et al. (1985) with an average of 9.5 southerly busters per year on the New South Wales coast of Australia over a 10-yr period. Note that the figures in New Zealand apply to a particular location and do not take account of the spatial nature and variation of wind changes. We also note that the use of hourly reports of 10-min mean wind speeds does not preclude much larger mean speeds between hourly reports and large gusts associated with the changes. It is well known that there can be large differences in the wind speeds observed at different locations for the same event; e.g., north of Christchurch at Kaikoura, southerly wind speeds frequently exceed those reported at Christchurch itself.

A large number of the events in the climatology of Ridley (1987) do not fit the southerly buster description. This is concluded also by Revell et al. (1987). They found that most southerly changes are associated with cold fronts originating over the southern ocean and accompany the passage of short-wave troughs in the westerly flow. Of the 10 examples they studied, only 2 obviously had a combination of abrupt wind change and sharp temperature drop, while some others produced just sharp strong wind changes. They found also that high prechange temperatures induced by foehn winds or other means lead to characteristically gusty changes, but that large density differences are not necessary for this. Thus there is interest in more than just the buster type of change.

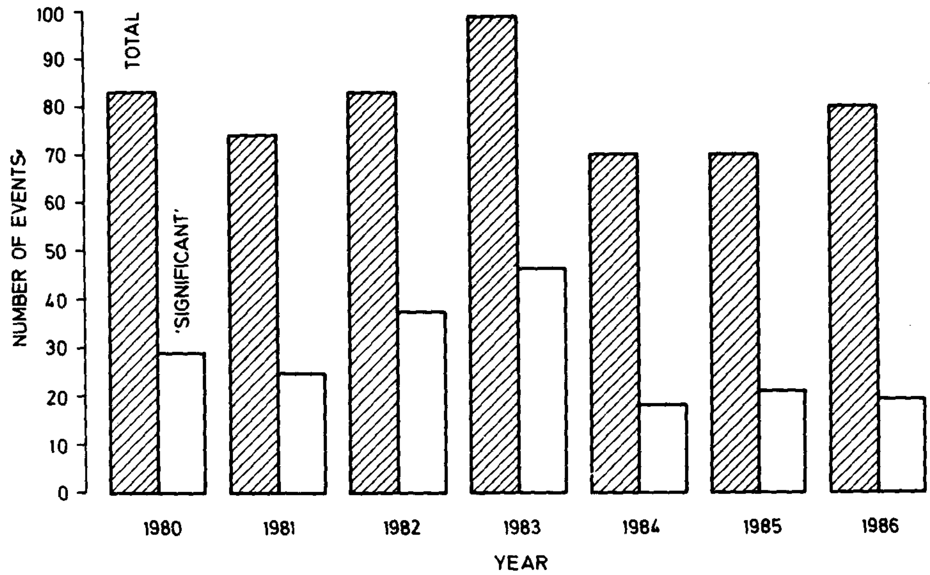

FIG. 3. The total number of events and the number of significant southerly change events at Christchurch from 1980–1986.

The climatology of Ridley (1987) provides also some information relating to the dynamics of southerly changes. Figure 3 shows the number of events and the number of significant events, for each of the years in the study period. Notably, the strengthening of the mean westerly flow over New Zealand during the prominent negative Southern Oscillation event of 1982–83 resulted in a marked increase (about 30% compared with other years) in the number of southerly changes during that period. This is entirely consistent with a greater frequency of short-wave features and associated synoptic-scale fronts crossing New Zealand. The proportion of significant events increased also, and this can be attributed to a higher frequency of foehn warming episodes, leading to larger temperature gradients associated with the southerly changes.

Figure 4 shows the annual variability in the number of significant and temperature events in a 28-day period commencing from the start date shown. There is a bias towards late summer and spring for significant events and towards the spring and summer months for temperature events. In January and February, almost all of the temperature events were also significant, i.e., of the southerly buster type. Thus significant and temperature events are favored by a larger land–sea temperature contrast.

Figure 5 shows the diurnal variability in the number of significant, temperature, and any type of event. Whereas events overall showed no preference for the afternoon and evening hours, significant and temperature events clearly favored these periods. Thus there is again an apparent strong correlation between the occurrence of significant (and temperature) events and the time of maximum land–sea temperature contrast.

Figure 6 shows the relationship between the prechange wind and the category of change. Over all the events, about one-third were preceded by foehn winds, whereas about 60% of significant events and 75% of temperature events were preceded by foehn winds. This suggests that the existence of northwesterly foehn winds is a typical characteristic of the synoptic setting in which these events occur, and that the resulting increase in temperature gradient across the change is important as already discussed in relation to Figs. 4 and 5.

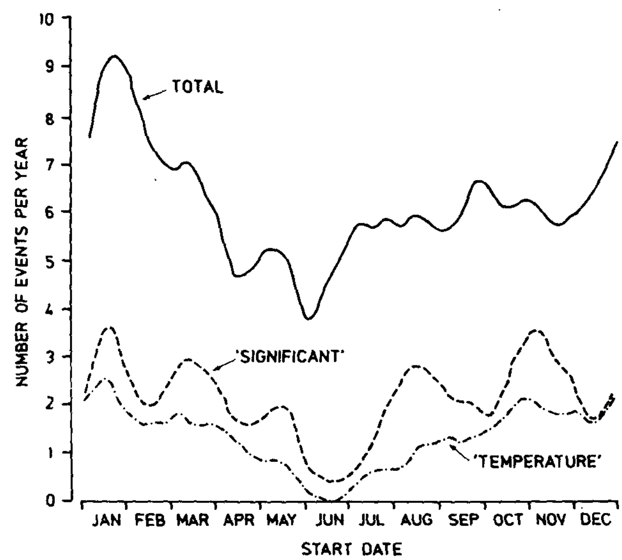

FIG. 4. The average number of significant and temperature southerly change events at Christchurch in 28-day periods commencing each day of the year; from the climatology of Ridley (1987).

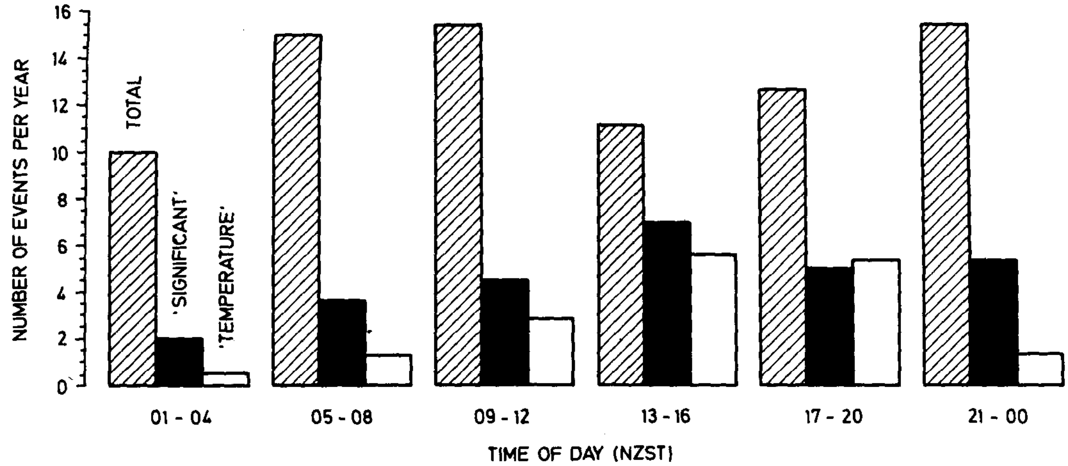

FIG. 5. The average number of all, significant, and temperature southerly change events at Christchurch, according to time of day; from the climatology of Ridley (1987).

The climatology found that thunderstorms were rare in association with any of the events (about 3%), and these were confined almost exclusively to the summer months and the afternoon hours. In only one case was such an event preceded by a foehn wind. Further, a large proportion of significant events were without associated precipitation. Revell et al. (1987) noted in their study that a wind change in this situation frequently becomes separated from the parent cloud system. Thus precipitating squall line characteristics are not a predominant feature of the southerly changes, and for the former to occur, moister onshore flow is a requirement as expected.

The climatology, along with logistical considerations, determined the timing of SOUCHEX from 14 January to 12 February 1988, a period during which between 3 and 4 significant southerly changes could be anticipated.

Ridley (1990) carried out a more specific study of the 27 events from his climatology that occurred in the time of year corresponding to SOUCHEX. He identified a number of changes with classical southerly buster characteristics and found common features in the associated synoptic situations leading to their formation. These common features included strong cross-alpine flow ahead of a wave in the prevailing westerly

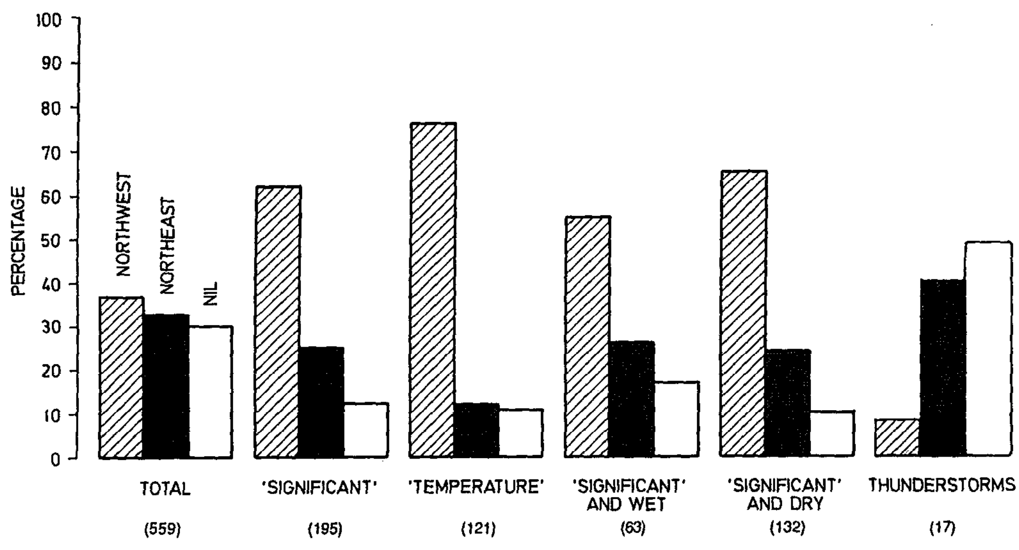

FIG. 6. The percentage of various categories of southerly change events at Christchurch with a prechange wind direction (within 12 h) from the northwest, the northeast (if northwest did not occur), or with no prechange wind (if wind < 5 m s^{-1}).

flow, a synoptic cold front approaching southern New Zealand, and much warmer than usual air prior to the change produced by foehn warming and, in some cases, by the origin of the air from over continental Australia (Fitzroy 1863). The latter confirms a study of Crawford (1977) on record high temperatures in eastern parts of New Zealand prior to a southerly change. Ridley (1990) found that stronger changes were associated with a relatively shallow southerly flow and larger cross-alpine pressure gradients and winds, and occurred at Christchurch close to the time of maximum land–sea temperature gradient. Two of the changes were examined in greater detail and exhibited a complex pattern of movement and evolution along the coast. Both reached their maximum intensity between Christchurch and Kaikoura, but were virtually nonexistent by the time they reached Cook Strait in the evening.

3. A synoptic summary of SOUCHEX events

Sequences of surface and upper-air analyses together with satellite images for each of the four principal SOUCHEX events are contained in the SOUCHEX report (Ridley et al. 1991). A brief description will suffice here. For the present we confine the description to broadscale aspects; vertical structure and mesoscale aspects will be considered in sections 4 and 5, respectively.

a. Event 1

This occurred on 14 January 1988 and was associated with a front of Southern Ocean origin embedded in a short-wave trough that crossed much of the country, bringing with it a deep air mass change. The routine analyses of the New Zealand Meteorological Service at 1300 NZDT[1] (0000 UTC) on this day are shown in Fig. 7 with the corresponding satellite imagery from the Japanese Geostationary Meteorological Satellite (GMS). The mean sea-level (MSL) analysis (Fig. 7a) shows the front at this time stretching west-northwest across the Tasman Sea from the middle of the South Island to southeastern Australia, although the precise location over the sea is obscured by a high-altitude band of cloud (Fig. 7c), presumably associated with the upper-level jet stream. Both north and south of the front, in a zone extending for several thousand kilometers from the south of Australia to New Zealand, the flow was unidirectional in a deep layer (Figs. 7a,b). The front separated relatively warm air originating over Australia from cooler air originating over the Southern Ocean. The situation was similar to those of 7 February 1973 (Crawford 1977; see also Fig. 2) and 27 January 1984 (Ridley 1990) when, on both occasions there was a 500-hPa flow with almost straight contours from southern Australia to the South Island preceding the change. In all three situations, there were high temperatures at the surface in eastern areas of New Zealand, and high free-atmosphere temperatures over New Zealand and the Tasman Sea. All these fronts were preceded by unusually warm conditions over Canterbury, presumably caused by the additional warming of an already warm prefrontal airflow by the foehn effect.

In the south of the South Island the frontal passage was accompanied by a period of rain with a pressure minimum and southwesterly wind change at the surface. Farther to the north, over the Canterbury Plains, the front was marked by a sharp change at 1330 NZDT from a strong gusty northwesterly foehn to an equally strong and gusty southerly followed by a rapid pressure rise, but there was no precipitation. Astonishingly, this change line, although one of the most intense of its type ever observed at Christchurch and Kaikoura, had weakened dramatically by the time it reached Cook Strait, only 100 km north of Kaikoura. A second change line, much weaker than the first, developed north of Dunedin and subsequently became the frontal passage observed along the east coast of the North Island, where it was marked by a weak wind shift that moved northeastwards overnight on 15 January. The Paraparaumu radiosonde sounding at 1300 NZDT showed that a relatively deep airmass change had reached the North Island with the trough.

b. Event 2

Prior to this event a depression formed over the Tasman Sea, and deepened as it crossed the South Island on 19 January. The situation at 1300 NZDT on 20 January 1988 is shown in Fig. 8. At this time the depression was centered near 50°S, 170°W and a cool southwesterly airstream had become established over and to the east of New Zealand. At upper levels there was a strong westerly airflow (Fig. 8b). The thickness pattern showed a significant gradient over the South Island towards the northeast and an upper-level cold pool lay just to the south of Invercargill (Fig. 8a), however, no surface front was evident at Invercargill. The satellite imagery (Fig. 8c) showed a band of high cloud extending on to the south of the South Island from the west, presumably associated with a strong upper-level westerly jet on the northern side of a cold pool. This band of cloud showed some development as it moved northeastwards over the country in association with the strong westerly upper-level flow ahead of a major trough.

A surface wind change was observed at Oamaru at 1200 NZDT accompanied by rain. No change was detected at reporting stations south of Oamaru. The change advanced northward reaching Christchurch during the evening and was accompanied by showers. It continued to move northward overnight, but re-

[1] Note that this is the New Zealand daylight time corresponding to the standard synoptic analysis time. Subsequent cross sections show balloon flights according to their time of release.

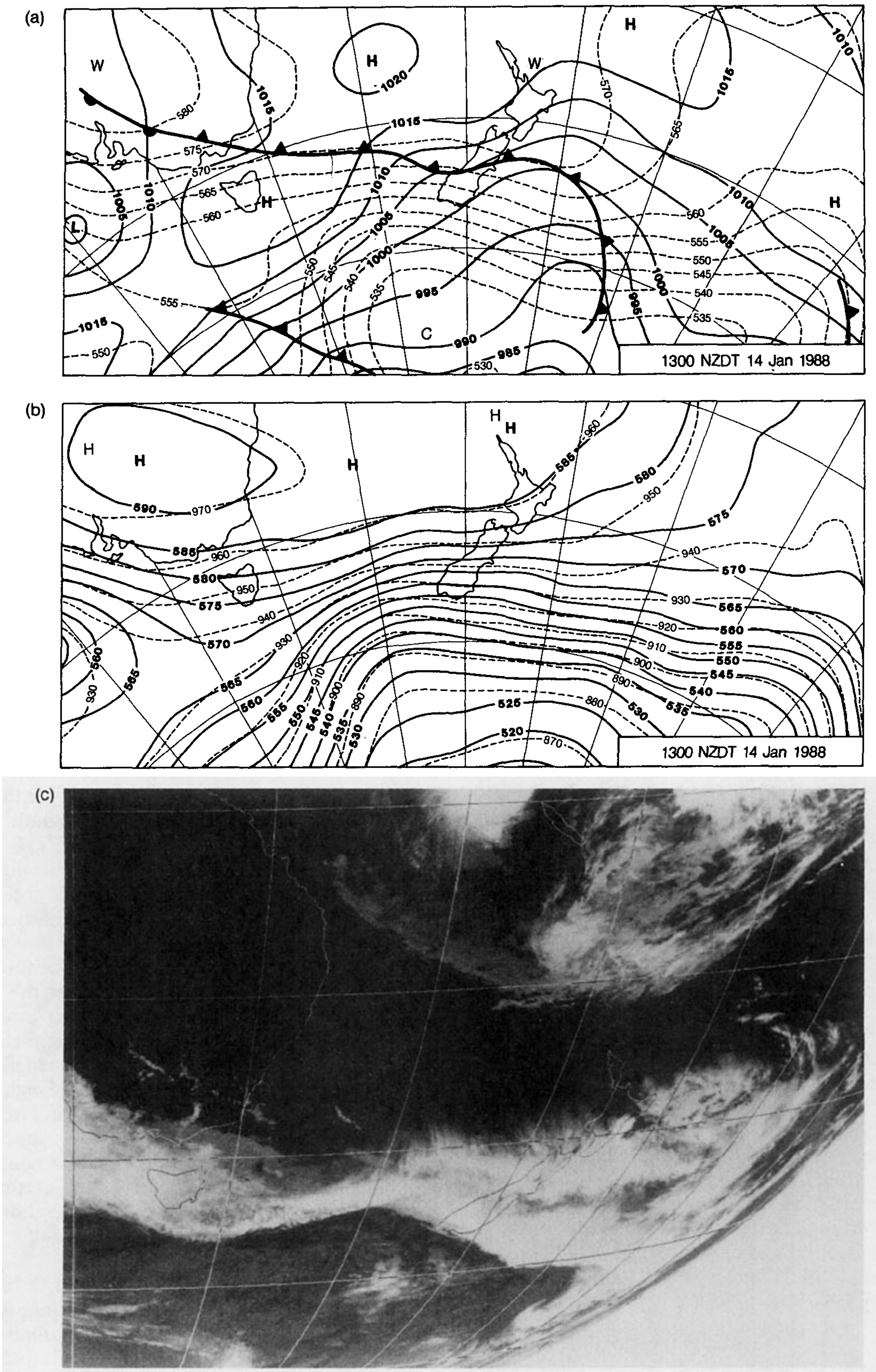

FIG. 7. The situation at 1300 NZDT 14 January 1988: New Zealand Meteorological Service analyses of (a) mean sea-level pressure and 1000–1500 hPa geopotential thickness (dashed), (b) 500-hPa and 300-hPa (dashed) geopotential height, and (c) infrared GMS satellite picture.

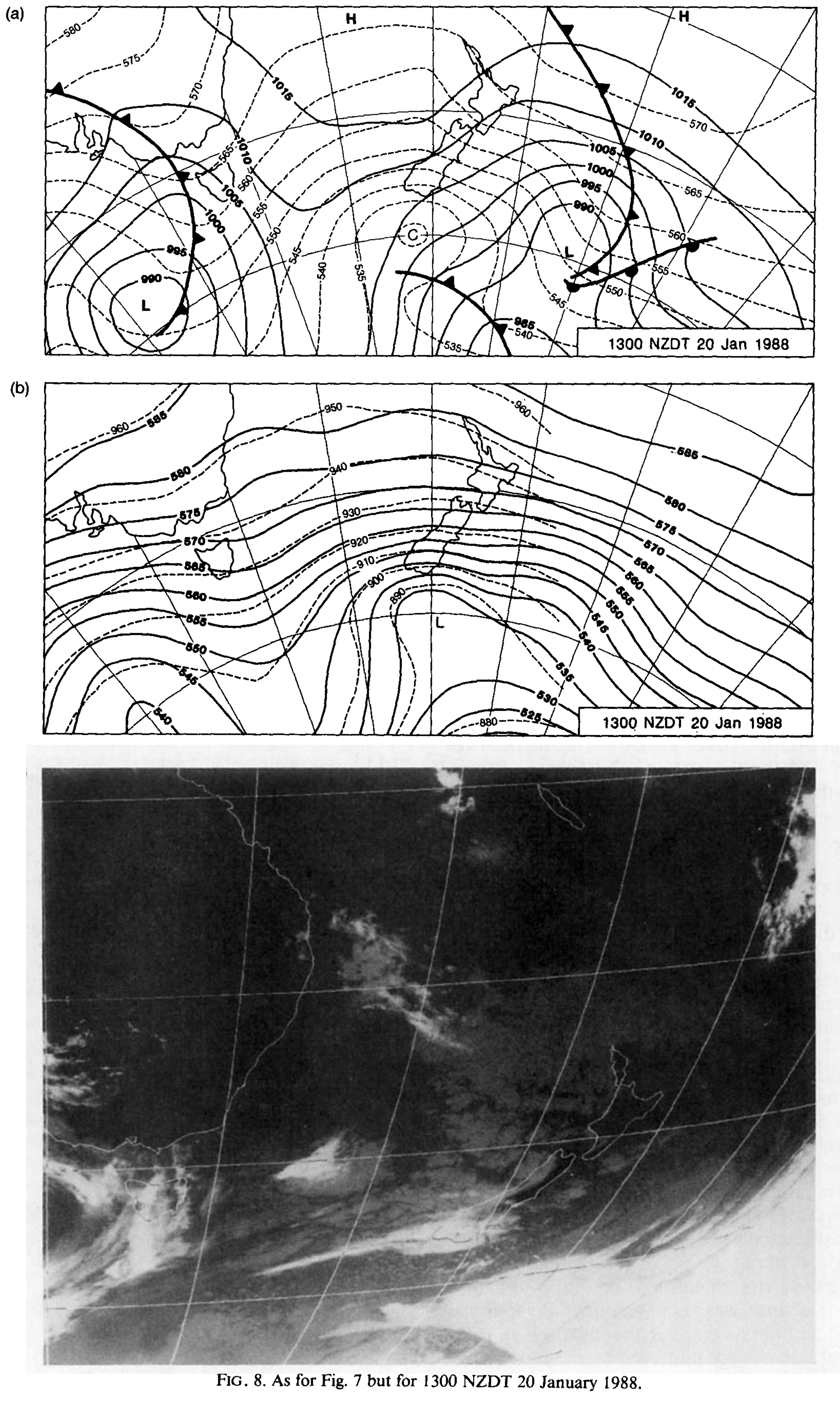

FIG. 8. As for Fig. 7 but for 1300 NZDT 20 January 1988.

mained relatively weak, and reached Gisborne at 1100 NDZT on 21 January. The surface wind change occurred some 150 km ahead of the rearward edge of the cloud band. Warm conditions did not occur in eastern areas prior to this change.

c. Event 3

This occurred on 26–27 January 1988 and like event 1 was preceded by warm conditions on the east coast, but in this case a strong and deep anticyclone was established to the east of New Zealand while a meridionally oriented front moved slowly across the Tasman Sea in association with a short-wave trough. During the morning of 26 January the front moved over the southwest of the South Island, accompanied by rain and a rise in the surface pressure. Its passage through Invercargill was complicated by a sea breeze, but was probably at about 1300 NZDT. The synoptic situation at this time is shown in Fig. 9. A band of upper cloud ahead of the surface front is evident in Fig. 9, while the upper-level trough lies well to the west of the surface trough axis. During the next 18 h a southerly or southwesterly wind change advanced along the east coast, reaching Christchurch shortly before 0100 NZDT and Kaikoura at 0520 NZDT, but it did not go beyond Cook Strait. The upper-level cloud band remained in existence almost 24 h after the surface manifestation of the front had disappeared. In this event the upper-level flow weakened as the front approached New Zealand and there was no well-defined passage of an upper-level trough over the country. Strong ridging persisted to the east and the trough over the Tasman Sea remained with its axis along 155°E.

d. Event 5

The synoptic conditions leading up to this event were similar to event 3 in that a meridionally oriented front lay across the Tasman Sea with a broad upper trough to the west of New Zealand. However, in this case a wave depression formed on the front southwest of the South Island. The synoptic situation at 0100 NZDT on 2 February is shown in Fig. 10. By this time there had been a well-defined wind change at Invercargill and Dunedin and the satellite picture (Fig. 10c) showed a band of middle-level cloud extending north-northwest across the South Island. The wind change reached Christchurch at 0700 NZDT accompanied by rain and a significant fall in temperature (~6°C in 2 h). The prechange conditions over Otago and Canterbury were relatively warm, although foehn winds did not penetrate to the surface at Christchurch. The change reached Cook Strait at about 1300 NZDT at which time a northwesterly jet-stream core was present over Christchurch. The change was very weak in the vicinity of Cook Strait and not detected farther north. Like event 3, this event was not accompanied by the passage of a well-defined upper trough. Indeed, the broad upper trough remained to the west of New Zealand as the front decayed over the North Island. During this time, the band of high cloud thickened considerably and was slow moving over the northern half of the South Island.

4. Vertical structure

During the SOUCHEX experiments, serial radiosonde, rawinsonde, and pilot balloon (pibal) soundings were carried out at a number of stations, mostly along the east coast, extending from Invercargill in the extreme south to Paraparaumu in the North Island (Fig. 1). The high frequency and spatial density of soundings are unprecedented in New Zealand and provide important new information concerning the vertical structure of southerly changes and the evolution in structure as the changes move northwards. Frontal evolution was documented also in terms of surface pressure time series obtained from an array of sensitive recording microbarographs installed at stations along the east coast of the South Island between Oamaru and Kaikoura (Fig. 1). These data are an important part of the present study and will be presented and interpreted event by event.

a. Event 1

Figure 11 shows time–height cross sections[2] of potential temperature $\theta(z, t)$ and equivalent potential temperature $\theta_e(z, t)$ constructed from the four radiosonde soundings at Invercargill between 2300 NZDT on 13 January and 14 January 1988, together with surface data derived from hourly observations. The frontal passage is ill-defined in the potential temperature cross section where an upper-tropospheric cold dome is the main feature, presumably associated with the passage of the upper-level trough (see Fig. 7). However, the equivalent potential temperature shows the cold dome to be associated with a pronounced air mass change in the lower troposphere through a sharp θ_e front extending from the surface at about 0800 NZDT to a height of nearly 8 km at 1700 NZDT. The surface change coincided closely with a shift in surface wind direction from westerly to southwesterly, but there was no very prominent change in the lower tropospheric wind structure between the prefrontal and postfrontal rawinsoundings at 0500 NZDT and 1100 NZDT, respectively (cross sections not shown).

At Christchurch, the situation was dramatically different. The potential temperature cross section (Fig. 12a) shows a sharp gradient in potential temperature in the lowest 3 km following the change, and this is reflected also in the equivalent potential temperature

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[2] This and subsequent cross sections are based on subjective analyses of surface and upper-air data.

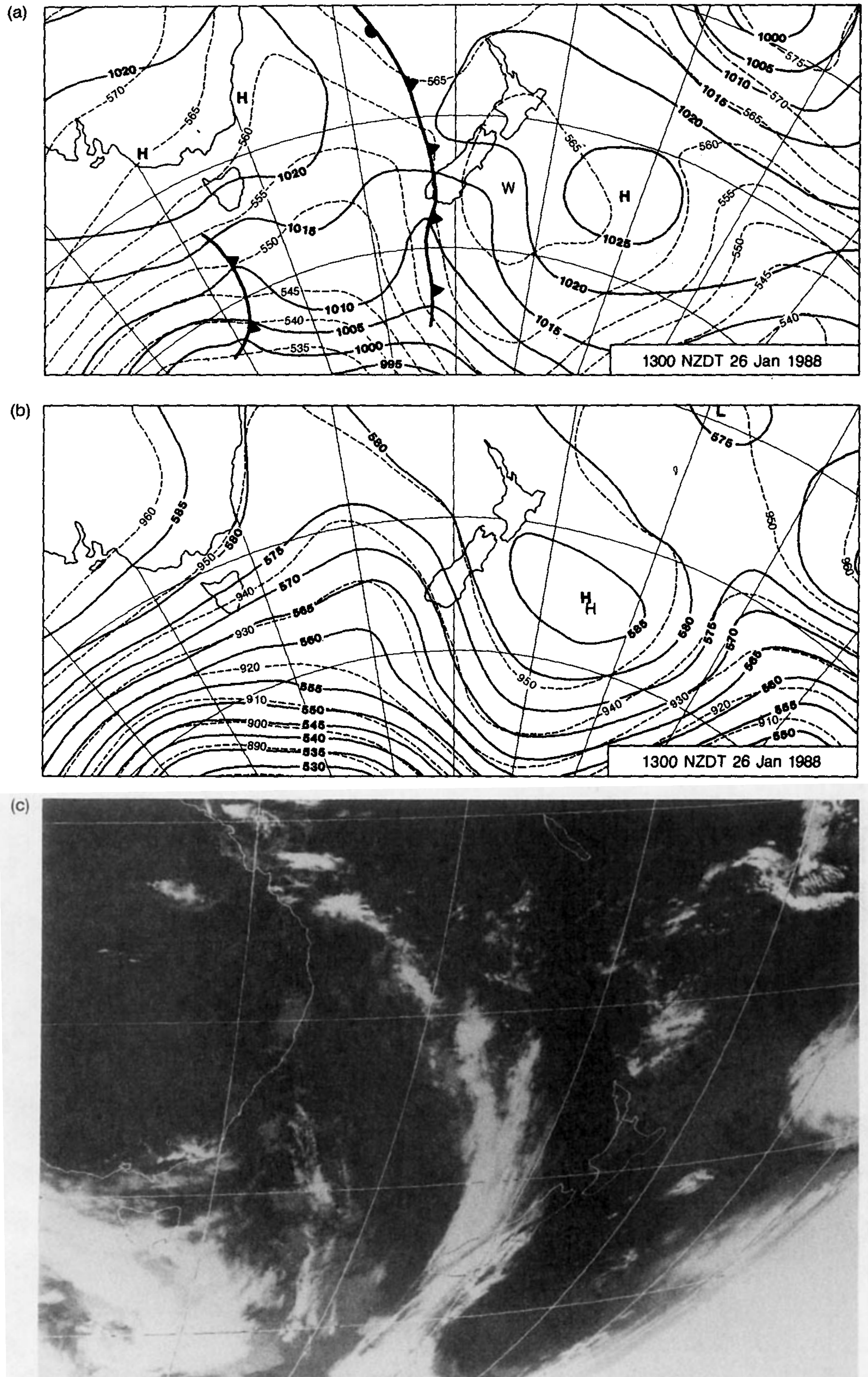


FIG. 9. As for Fig. 7 but for 1300 NZDT 26 January 1988.

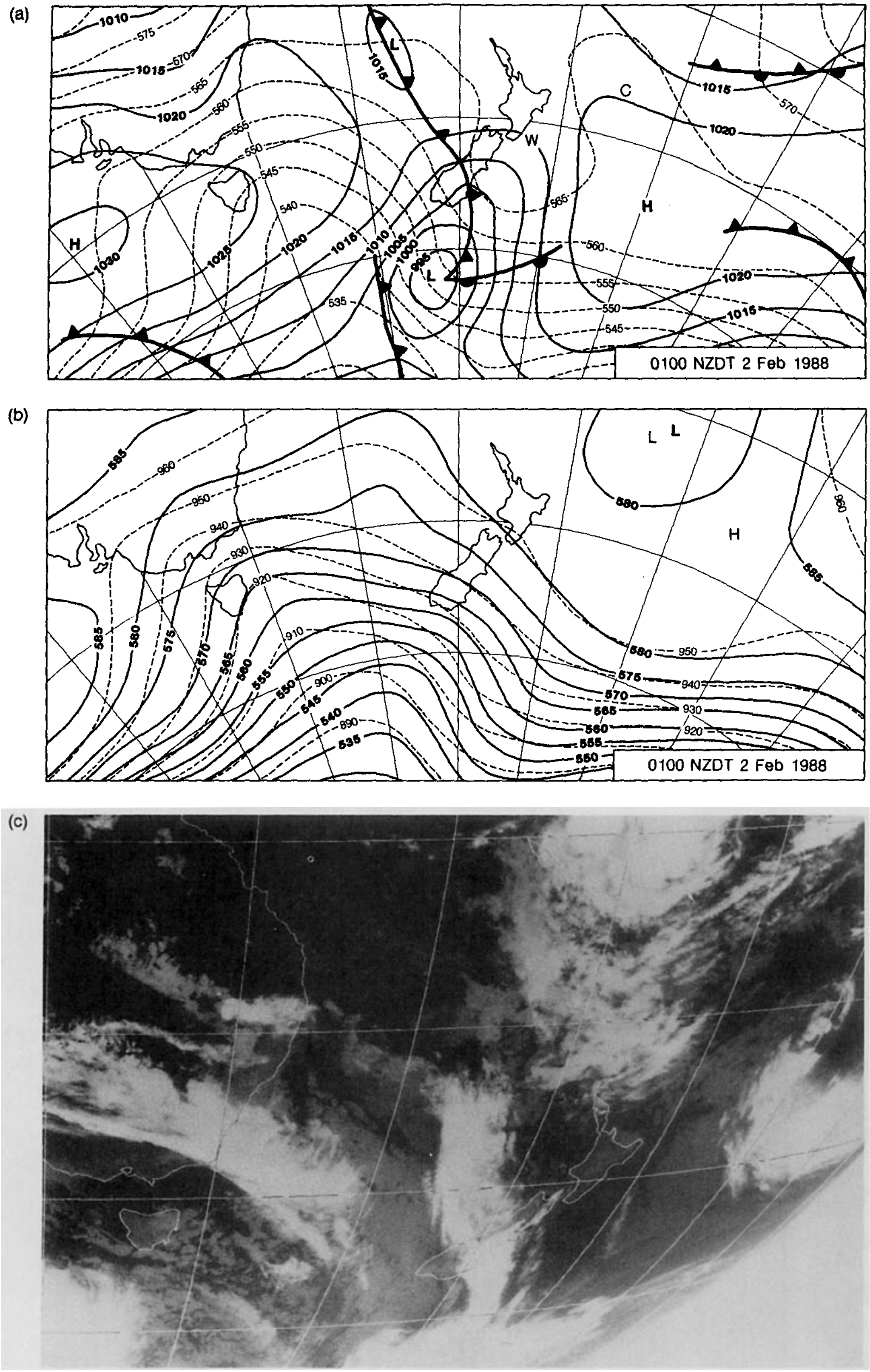


FIG. 10. As for Fig. 7 but for 0100 NZDT 2 February 1988.

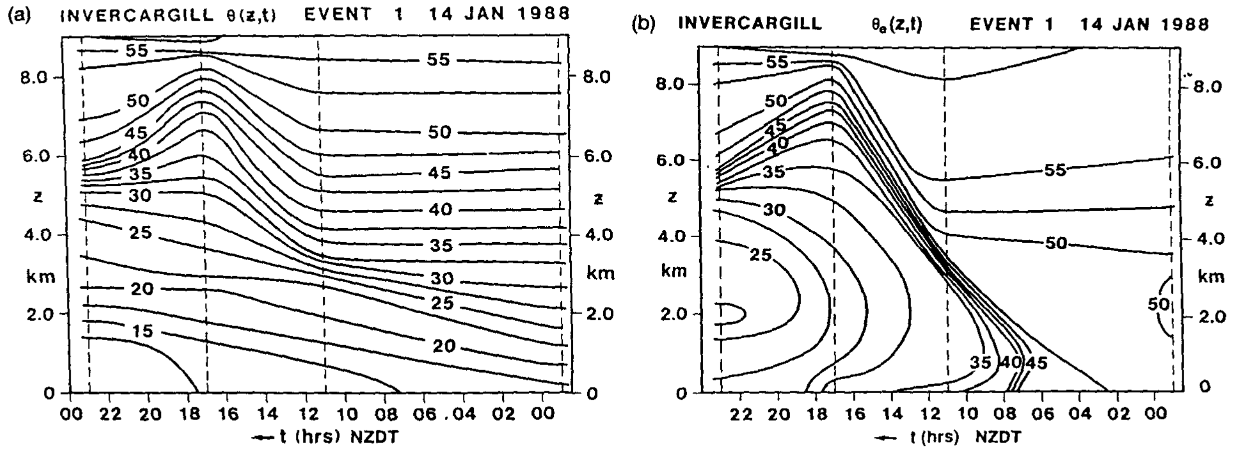


FIG. 11. Time–height cross section of (a) potential temperature $\theta(z, t)$; and (b) equivalent potential temperature $\theta_e(z, t)$ at Invercargill for event 1. The vertical dashed lines indicate the balloon soundings. Note that for this and subsequent cross sections the time scale runs from right to left to give the correct sense of the spatial structure.

(Fig. 12b), although the structure of the θ_e cross section is rather more complicated in this case. Nevertheless, both sections are suggestive of a moderately deep air mass change, albeit shallower than had occurred at Invercargill. Ahead of the change, surface temperatures reached 29°C, falling to 20°C in less than an hour.

It is interesting to compare these changes with those in the wind components (Figs. 12c,d). The high prefrontal temperatures were associated with foehn conditions in a generally northwesterly airstream with a prominent maximum in the westerly component exceeding 20 m s^{-1} below about 1 km (Fig. 12c). With the passage of the front the northwesterlies were replaced by southerlies at low levels (below about 1 km), the maximum also exceeding 20 m s^{-1} (Fig. 12d). It is noteworthy that the surge of southerly component winds and the cooling following the sharp surface wind change was very shallow with northwesterlies above about 1 km over Christchurch. The southerly winds extended to a level well below the mean ridge level of the Southern Alps to the west, but the cooling evidenced in the θ and θ_e cross section extended more deeply, however, indicating that potentially cooler and dryer[3] air was crossing the mountains from the northwest to west following the southerly change at low levels. In particular, the sharpness of the front in θ between 1 and 3 km is probably attributable to the collapse of the foehn with the change, or more precisely with a restructuring of the cross-mountain flow.

A further notable feature of the disturbance was its relatively short duration. At Christchurch, the southerly wind component at low levels was reversed at approximately 1720 NZDT when a period of northeasterlies set in. This short duration of the southerly surge was a characteristic at all stations along the east coast north of Oamaru and is exemplified by the surface wind variation of Christchurch and Kaikoura (Fig. 13). A second and more prolonged period of southerly wind component became established several hours after the demise of the initial surge with onset occurring at Christchurch at about 1815 NZDT and at Kaikoura at about 2100 NZDT. Subsequently we refer to this as the second change of event 1.

Comparison of the wind changes with surface pressure are particularly revealing for this event and highlight the continuing strong interaction between the cross-mountain flow and the near-surface flow in the lee of the mountains following the change. The surface pressure changes obtained from the CSIRO microbarometers at Oamaru, Christchurch, and Kaikoura[4] for event 1 are shown in Fig. 14. All three stations show a sharp pressure rise with the onset of the change and each shows an equally strong fall some 3–4 h later. At Oamaru the pressure soon recovered after the fall,[5] while at Christchurch and Kaikoura it did not. Moreover, the duration of the anamolously high pressure decreased as the disturbance moved northwards across the barometer network. At Christchurch the sharp pressure rise commenced at 1332 NZDT and lasted for 15 minutes, while the surface wind change occurred at 1340 NZDT. At Kaikoura, there were two very pronounced wind surges, the first at 1505 NZDT from the west-southwest and the second at 1600 NZDT from the south-southwest. Surprisingly, there was no rise in

[3] Drying out was indicated clearly in the mixing ratio cross section, which is not shown here.

[4] Unfortunately, no data are available from the other microbarograph stations for this event.

[5] Pressure sampling occurred at 1-min intervals so that the fall and recovery at Oamaru is well resolved.

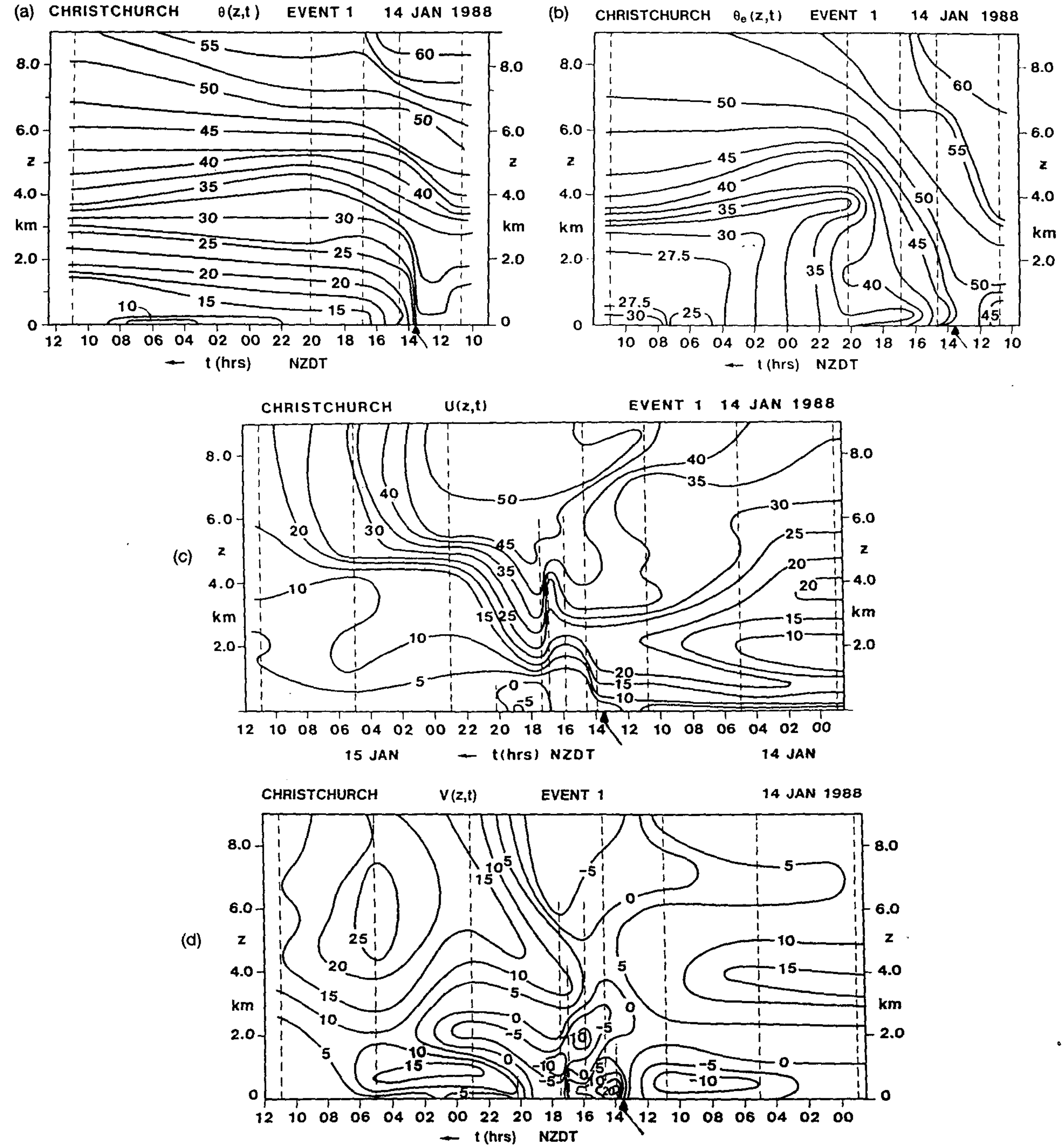


FIG. 12. Time-height cross section of (a) $\theta(z, t)$, (b) $\theta_e(z, t)$, (c) the westerly wind component $U(z, t)$, and (d) the southerly wind component $V(z, t)$ at Christchurch for event 1.

surface pressure corresponding with the first wind surge at Kaikoura; indeed shortly afterwards the pressure fell slightly, and there was little temperature or humidity change. There the sharp pressure rise does not begin until 1608 NZDT, just after the onset of the second wind change. We have interpreted this second surge at Kaikoura as the first change of event 1, which passed through Christchurch.

Referring back to Fig. 12d we note that, at Christchurch, the sharp fall in pressure at about 1715 NZDT coincided with the final collapse of the initial southerly surge and that this was associated with a sudden

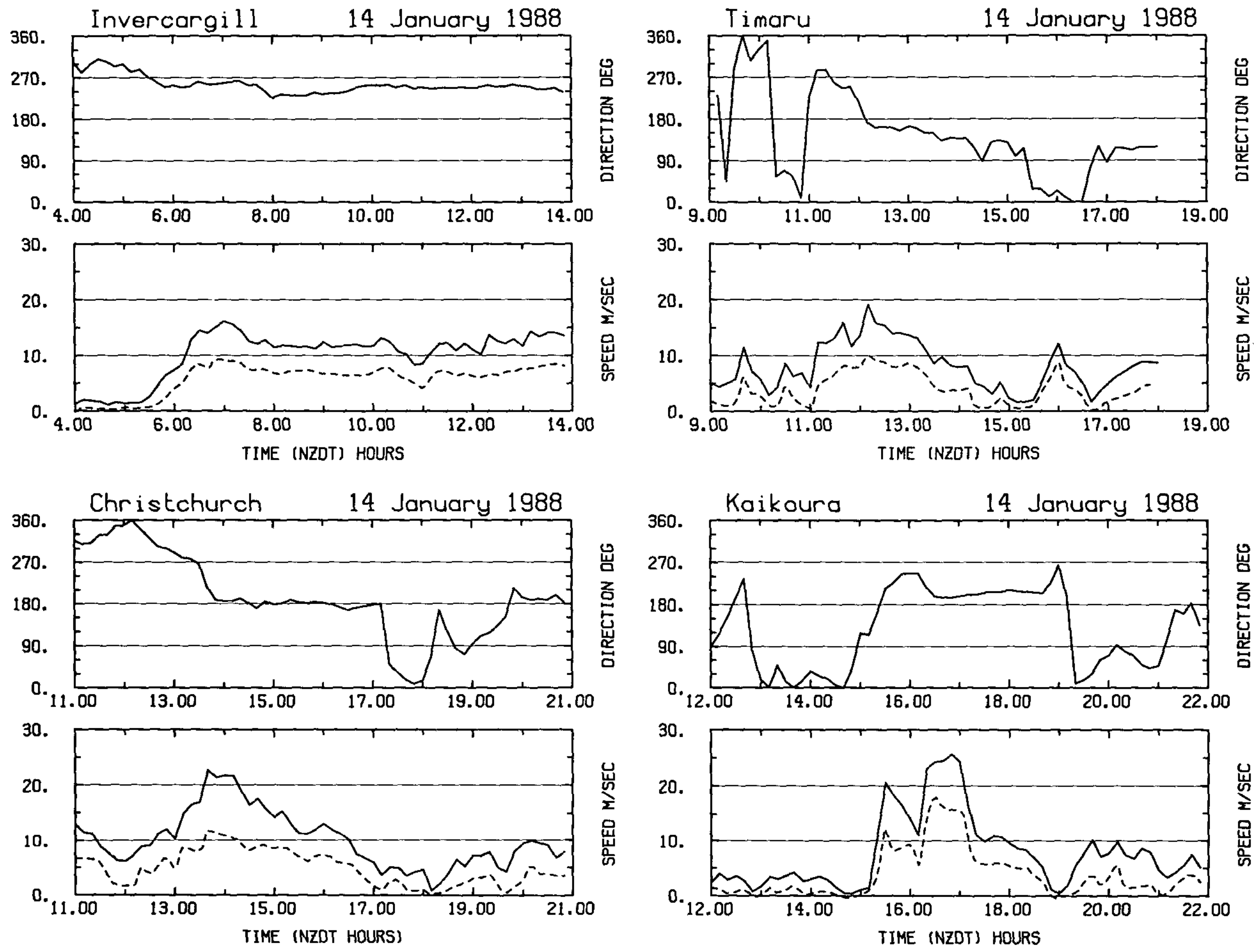


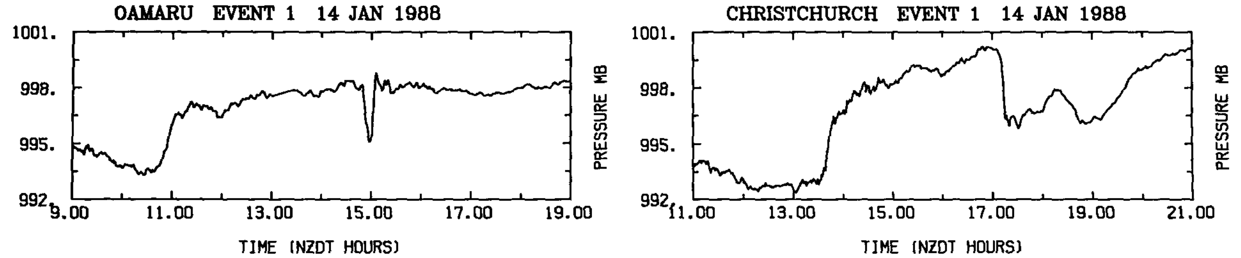
FIG. 13. Surface wind variation at Invercargill, Timaru, Christchurch, and Kaikoura during event 1. The figures are constructed from digitized 10-min averages of anemograph traces. The wind speeds shown are the average maximum (solid lines) and average minimum (dashed lines) values and the separation of these two curves is a measure of the gustiness.

strengthening of the westerly wind component at heights between about 2 and 5 km.[6] This strongly suggests that the pressure fall and the consequent response of the low-level wind field was associated with a restructuring of the cross-mountain flow due, presumably, to a rapid change in the upstream flow conditions, brought about by the movement of the upper trough. Unfortunately, there are no wind soundings available from the western side of the mountains to verify this scenario.

The occurrence of the initial wind surge at Kaikoura, unaccompanied by a significant pressure or temperature change, may have been produced also as a response of the low-level flow to a restructuring of the cross-mountain flow. This could have led to a geographically fixed[7] change in the surface pressure pattern on the mesoscale and therefore to a local acceleration of the flow, or simply to the downward transport of momentum with a southerly component. In this connection we note that at Christchurch the cross-mountain winds had a significant southerly component between 3 and 5 km prior to the change. Again, data are lacking to properly assess these possibilities, but it is not easy to imagine other mechanisms that would produce such a strong wind surge without an accompanying pressure change. Currently we are carrying out related numerical model calculations to explore the efficacy of such processes.

[6] Without the sharp surface pressure fall that occurred between the rawinsoundings at 1653 and 1722, one might have been disinclined to believe the large change in the westerly wind component between these heights as representative.

[7] In comparing the wind changes at Kaikoura and Christchurch, the different topography of the two places should be kept in mind—Christchurch is on the open plain, while Kaikoura is where the mountains extend right to the coast.



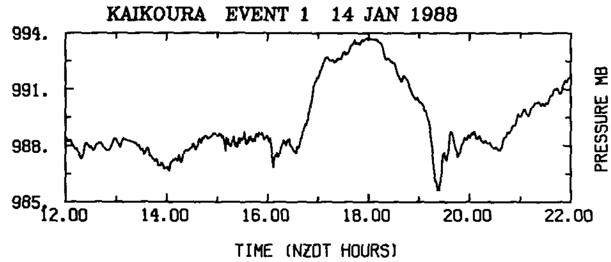


FIG. 14. Surface pressure variation at Oamaru, Christchurch, and Kaikoura during event 1. The data are from microbarometers kindly provided by the CSIRO Division of Atmospheric Research.

At this point it seems worth drawing attention to a recent numerical study of the airflow over a mountain by Lee et al. (1989) that is relevant to the foregoing situation. These authors showed that the presence of a cold pool of air in the lee of the mountain changes the effective mountain shape and may effectively suppress the formation of a large amplitude mountain wave. Their study was motivated by the situation in the lee of the Rockies when cold Arctic air lies in a shallow layer to the east and the upstream flow is such that it would otherwise excite a large mountain wave accompanied by strong downslope winds. Interest was centered on the conditions under which the cold air near the mountain would be flushed out by the development of such winds. This situation is clearly similar to that described above in which the shallow layer of cold postfrontal air may be expected to produce a similar change in the structure of the cross-mountain flow, depending on the characteristics of the upstream flow and on the depth, stability, and flow within the cold air. Recall that the upper-level cross-mountain flow at Christchurch in event 1 remained long after the passage of the front (Fig. 12).

b. Event 2

Figure 15 shows time–height cross sections of θ_e, u, and v at Invercargill between 1100 NZDT on 20 January 1988 and 1100 NZDT on 21 January 1988. A prominent feature is the upper-level cold pool apparent at 1700 NZDT (Fig. 15a), consistent with the replacement of a strong westerly jet near 8 km at 1100 NZDT (Fig. 15b) with a weaker southeasterly upper-level flow at 2300 NZDT (Fig. 15c). As remarked in section 3, there was no obvious passage of a surface front. However, frontogenesis was initiated along the east coast as the upper trough moved northwards. The corresponding time cross sections of θ_e, u, and v at Christchurch are shown in Fig. 16. As in event 1, a deep airmass change is indicated by the changes in θ_e and this is evidently associated with the passage of the cold pool. Also, as at Invercargill, the cold dome in Fig. 16a at 0500 NZDT on 21 January follows the passage of a strong westerly jet in the early hours. At Christchurch the upper winds behind the cold pool were southwesterly rather than southeasterly, suggesting that the cold-pool center passed to the east of Christchurch. The southerly change occurred shortly after 2000 NZDT and as in event 1 was relatively shallow, never exceeding 2 km, with northwesterly winds persisting aloft for many hours after the change. However, unlike the first event, the change was preceded by a shallow northeasterly flow, and the northwesterly flow above this was lighter. Surface pressure changes accompanying the southerly flow were relatively unspectacular and were dominated by a general rise related to synoptic-scale changes.

c. Event 3

Figure 17a shows the time–height cross section of θ_e based on the five radiosonde soundings at Invercargill between 1100 NZDT on 26 January and 1100 NZDT on 27 January, again with data derived from hourly surface measurements. Like events 1 and 2, an upper-level cold pool was in evidence and as in event 1, this was connected with a sloping frontal zone of relatively large θ_e gradient, indicative of a change in air mass. This zone passed at the surface between 1400 NZDT and 1600 NZDT. The main surface wind shift at Invercargill occurred at 1140 NZDT, when the wind direction changed sharply from west-southwest to south, but this may have been associated with a sea breeze.

At Christchurch, the θ_e cross section (Fig. 17b) shows

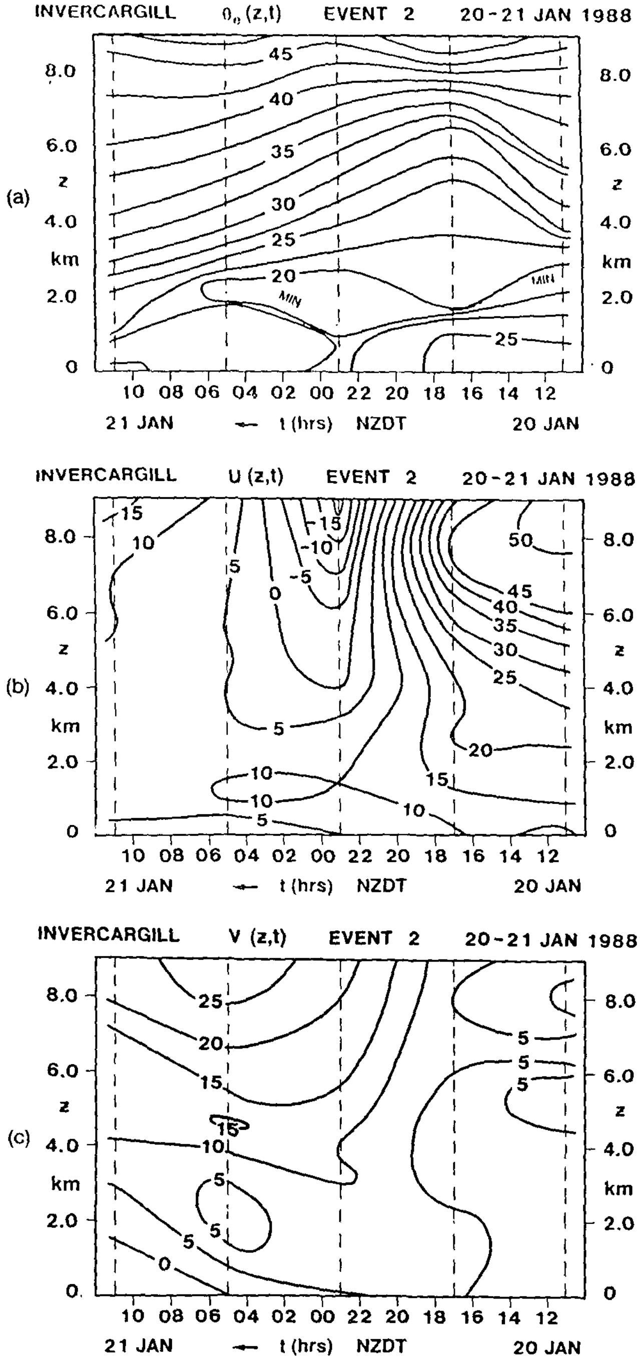


FIG. 15. Time–height cross section of (a) $\theta_e(z, t)$, (b) $U(z, t)$, and (c) $V(z, t)$ at Invercargill for event 2.

evidence of a deep airmass change commencing in the early hours of 27 January, but the zone of large θ_e gradient is not so pronounced below 1 km. In contrast, the wind change from a relatively weak northwesterly to a moderate southwesterly, was confined below 1 km as shown in Fig. 18. The latter feature is based on serial pibal soundings together with the 0500 NZDT rawinsounding.

d. Event 5

Figure 19 shows time–height cross sections of θ and θ_e from the five radiosonde soundings at Invercargill between 1100 NZDT on 1 February and 1100 NZDT on 2 February 1988. In this case the frontal zone is clearly evident in both the θ and θ_e cross sections where

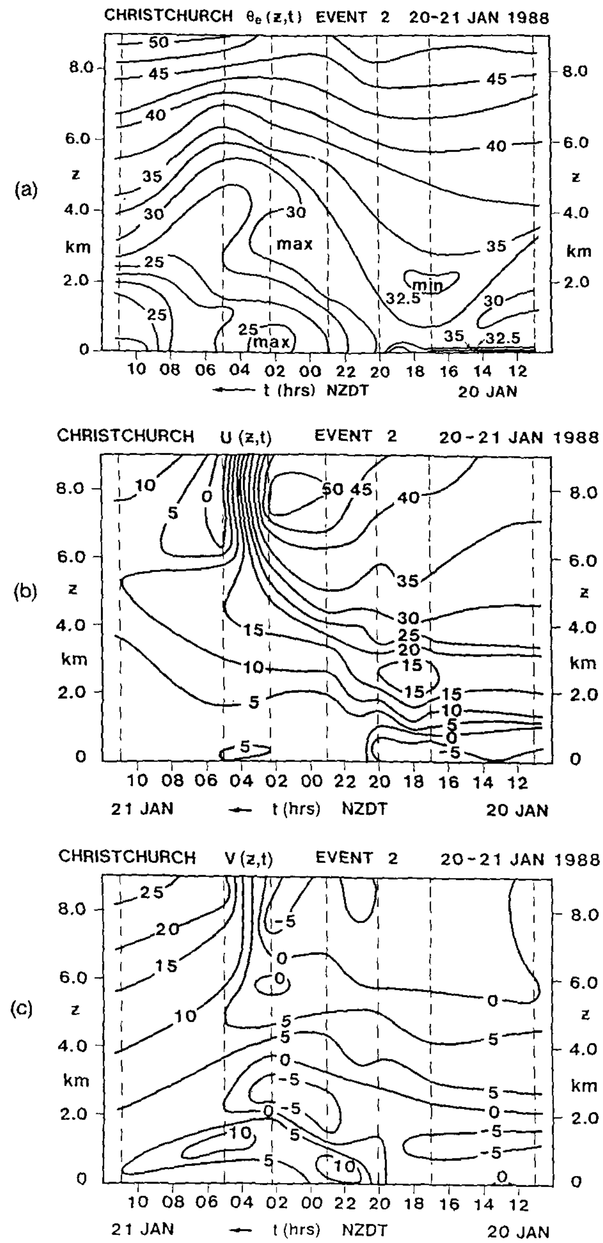


FIG. 16. Time–height cross section of (a) $\theta_e(z, t)$, (b) $U(z, t)$, and (c) $V(z, t)$ at Christchurch for event 2.

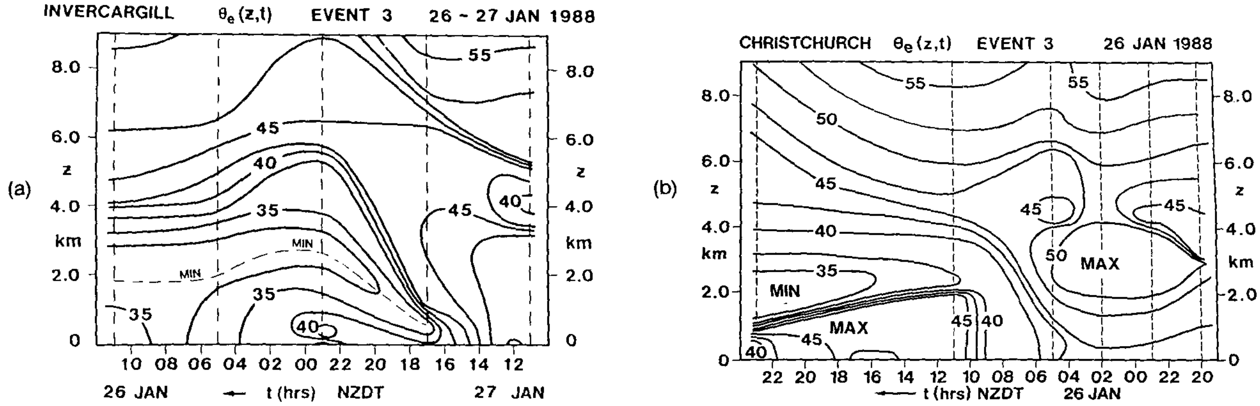


FIG. 17. Time–height cross sections of $\theta_e(z, t)$ for event 3 at (a) Invercargill and (b) Christchurch.

strong low-level cooling occurs between 2100 NZDT and 2200 NZDT with a correspondingly large fall in θ_e just after 2200 NZDT. The latter coincided closely with a surface wind shift from northwesterly to south-southwesterly, which was accompanied by a sharp increase in wind speed. Judging from the isentrope cross section (Fig. 19a), the front was relatively shallow, the height of the postfrontal inversion remaining about 2 km between 6 and 12 h after the passage of the surface front. The deeper frontal zone in the θ_e cross section was associated with a middle-tropospheric dryline or zone indicative of large-scale subsidence in the middle and upper troposphere after the frontal passage.

Cross sections at Christchurch of θ_e and isotachs of u and v constructed from three rawinsoundings and nine pibal soundings are shown in Fig. 20. The frontal passage, as marked by the surface wind change, occurred at about 0700 NZDT, although the wind built up slowly in strength over about 20 min. During this period, θ_e declined rapidly marking clearly the frontal zone in the lower atmosphere. Like all the previous events, the depth of the postfrontal southerlies was little more than 1 km, and like events 1 and 3, the front was preceded by a northwesterly foehn (Figs. 20b,c).

5. Mesoscale aspects

The mesoscale surface observation network operated during SOUCHEX is described by Sturman et al. (1990). The additional surface observations were made, especially over Canterbury, to investigate the inland movement of wind changes and the penetration of air into the alpine valleys on the eastern side of the Southern Alps. A common feature of the isochrones of the surface wind change for all events was the tendency for the change to line itself up with the direction of the coast. This is exemplified by the isochrones of the first wind change of event 1 and the wind change of event 5 shown in Fig. 21. Overall, the speed of inland penetration of the air following the changes was on the order of 3–5 m s^{-1}, while the speed of the changes along the coast was on the order of 10–20 m s^{-1}. Only in event 5 were there data available to determine the position of the change offshore. In this case, observations from the aircraft and the ship (up to 100 km from the coast) suggest that the change line moved faster along the coast to the north of Christchurch than at the corresponding positions offshore, particularly north of Kaikoura where the mountains meet the sea.

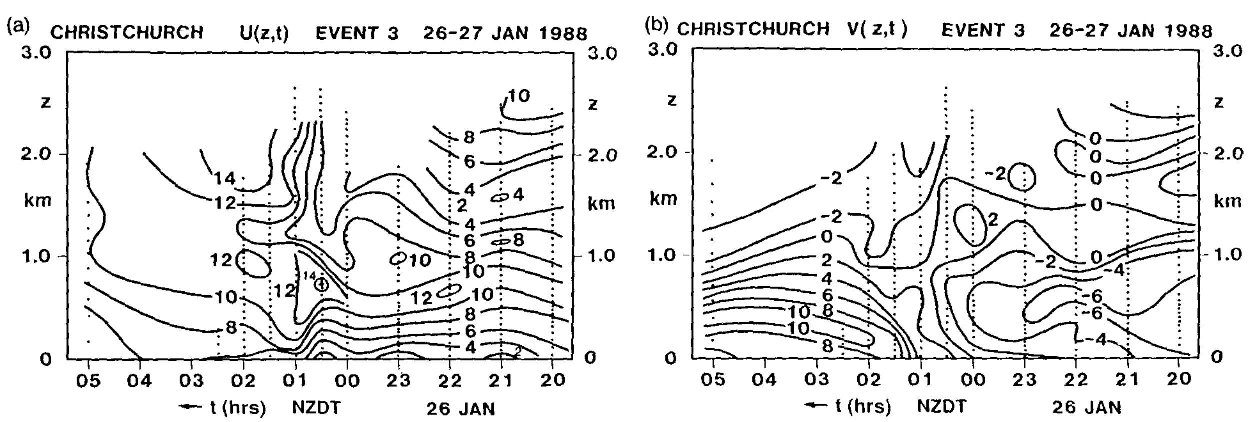


FIG. 18. Time–height cross sections of (a) $U(z, t)$ and (b) $V(z, t)$ at Christchurch for event 3.

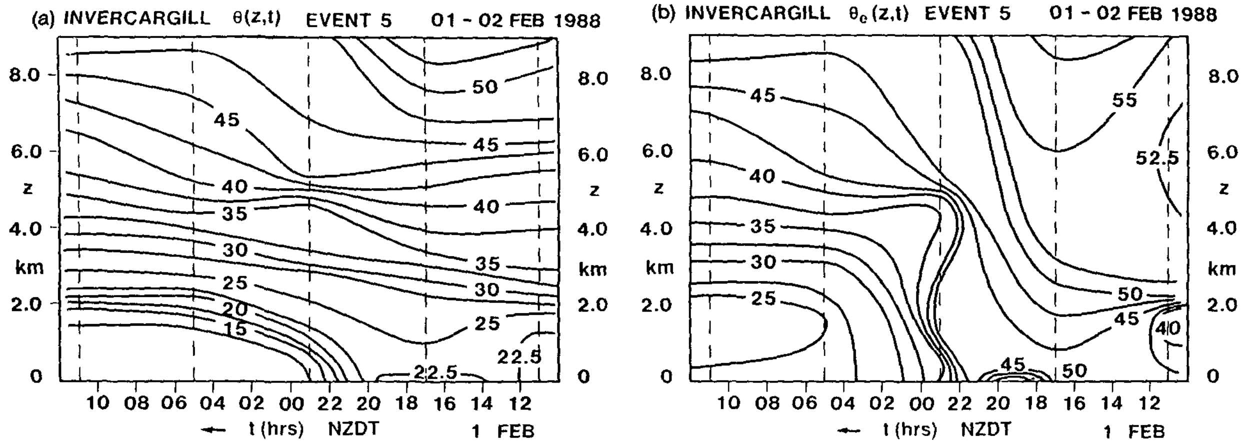


FIG. 19. Time–height cross sections of (a) $\theta(z, t)$ and (b) $\theta_e(z, t)$ at Invercargill for event 5.

The coastal end of the change then appeared to decelerate in the vicinity of Cook Strait allowing the offshore portion to catch up, although the subsequent behavior of the offshore end of the change is unclear due to the sparsity of the data. This type of deformation of the front is in contrast to that found for southerly busters along the southeastern seaboard of Australia (Colquhoun et al. 1985). Aircraft observations in their Fig. 8 suggest that the change line was perpendicular to the coast, although in that case the offshore data were fairly sparse also. In particular, the isochrones on their Fig. 15 (for a different event) are not inconsistent with those observed in this study.

The relatively slow inland penetration of the changes is consistent with the shallowness of the cold-air surge, the gentle upward slope (typically 1 in 150) of the inland plains, and the fact that, except in Event 2, there remained a considerable cross-mountain flow for some hours after the change had passed. The westerly or northwesterly flow was inclined to persist in the alpine valleys, leading to considerable complexity of the postfrontal airflow over the Plains near the valley exits. Sturman et al. (1990) found that the airmass change in the valleys occurred in some cases as a series of minisurges as the cross-mountain flow was displaced.

It seems likely that the intensity of event 1 was attributable at least partly to the presence of adiabatic heating of an already warm air mass in the prefrontal foehn, together with diabatic heating over the Canterbury Plains, which led to a relatively large temperature gradient across the surface front. Over the plains, surface temperatures reached 30°C before the change, whereas sea temperatures off the coast were on the order of 13°C. It seems likely, also, that the occurrences of events 3 and 5 were contributed to by foehn warming of the prefrontal air. However, both these changes crossed the plains when diabatic heating was not occurring, and this may account, at least partially, for their lesser intensities.

A prerequisite for a cold front to have the local structure of a gravity current is the existence of a region of positive relative flow (i.e., towards the front) near the surface in the cold air, at least above a shallow frictional layer (Smith and Reeder 1988). Information on the relative postfrontal airflow in the SOUCHEX events ($u' - c$) is presented in Table 1, u' being the maximum wind speed component in the assumed direction of movement of the change and c the speed of the change. Surface data from Timaru (TU) and Kaikoura (KI) were used to estimate c, while u' was determined from the wind soundings at Christchurch (CH). There are inherent difficulties in making these calculations since sufficient data were not available to determine the precise orientation of the changes as they passed Christchurch, and wind soundings were for varying elapsed times after the changes. Thus in Table 1 we present the calculations assuming the movement is parallel to the coast (TU − KI) or from the south. We note also that Banks Peninsula, rising to almost 1000 m, may have had a significant effect on the changes as they passed Christchurch due to the relatively shallow (1–2 km) southerly flow. Data for the Winchmore (WI) acoustic sounder are available also for events 1, 2, and 5, however we have used Christchurch soundings for the estimation of u', as Winchmore is some distance inland and the isochronologies suggest that the direction of movement of the changes would be somewhat different there. This is shown by figures in the final column of Table 1, which indicate that the low-level winds (<600 m) at Winchmore had a significantly greater easterly component than at Christchurch. Notwithstanding these difficulties, the table shows that the leading wind changes in event 1 and event 3 both apparently contained some region of positive relative flow as was found also in case studies of the southerly buster in Australia (Coulman et al. 1985). This is an indication that these changes had locally the characteristics of, at least, an unsteady grav-

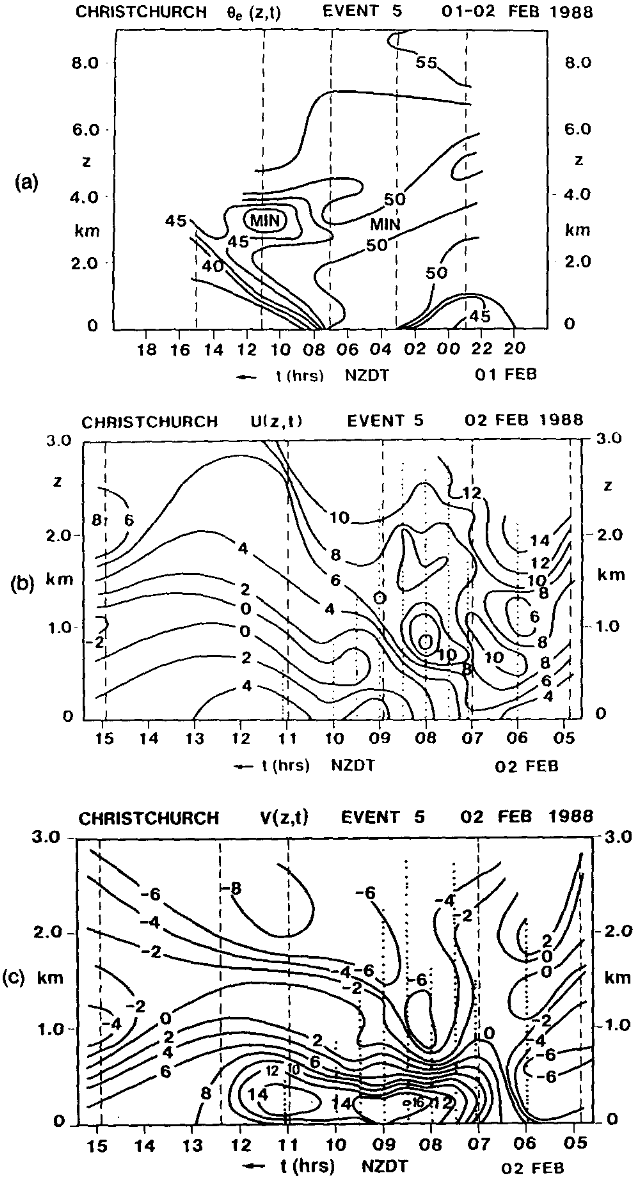


FIG. 20. Time-height cross sections of (a) $\theta_e(z, t)$, (b) $U(z, t)$, and (c) $V(z, t)$ at Christchurch for event 5.

ity current (Smith and Reeder 1988). The second change of event 1 appears to have contained no region of positive relative flow although the earliest postfrontal sounding was some 2 h after the change. The situation for event 2 is not clear, as the interpretation depends on the assumed direction of movement. For event 5, positive relative flow was not present immediately following the change (0705 NZDT sounding), but may have occurred at later times, depending on the assumed direction of movement.

We have reservations in applying the usual formula relating the speed of a steady, nonrotating gravity current to the temperature contrast across the front and the depth of the cold air [see, e.g., Smith and Reeder 1988, Eq. (3.3) or Eq. (3.5)]. Unsteadiness was a characteristic of all the events, and the time taken for the surges to traverse the east coast was comparable with at least one-quarter of an inertial period (about 5 h), whereupon Coriolis forces may not have been negligible. However, it would be reasonable, and indeed dynamically consistent, to assume a monotonic increase in the speed with an increase in the temperature difference across the front. Observations in two southerly busters in the Australian region support this contention (Coulman et al. 1985). The first change of event 1 reached Christchurch within 6 h of the frontal passage at Invercargill, while the second change of this event took about 12 h, and those of events 3 and 5, which had a more northerly orientation than event 1, took 13 h and 9 h, respectively. Although the intensity and speed of the initial change of event 1 is likely to have been contributed to by its associated temperature contrast, this does not seem a sufficient explanation; similar temperature gradients in previous buster type events have not necessarily resulted in such high speeds (Ridley 1990; Revell et al. 1987). However, as noted in section 4, the winds over Christchurch between 3–5 km remained southwest throughout event 1 (Fig. 12), with speeds in excess of 25 m s^{-1}. Thus, in this case, there was a significant along-mountain component of the wind just above mountain-top level in the direction of movement of the change, even though the lower-level prechange winds were from the northwest. Such a wind structure stands this event apart from other buster-type changes, where the winds near mountain-top level and above are generally northwest (Ridley 1990) and might have been a contributing factor to the large speed in Event 1.

Finally in this section we note that the high time resolution of the acoustic sounder data from Winchmore showed that the southerly wind changes were vertical through the 600–900 m layer sampled, but there was not always a single direction change. For example, the initial change of event 1 was preceded by a clearly defined 2-h period of near-surface westerly flow after the earlier north-northwesterly flow. Also in event 5, a short ($\sim$1 h) period of southwesterly winds ($\sim$6 m s^{-1}) occurred before the shift to south-southeasterlies ($\sim$16 m s^{-1}), the latter corresponding to the change of event 5 observed at other sites. On its own, the high time resolution data from Winchmore has limited application in the context of this study, however the data will be useful for verifying future numerical experiments on southerly changes.

6. Discussion

A common feature of the four main SOUCHEX fronts was the initial shallowness of the southerly flow

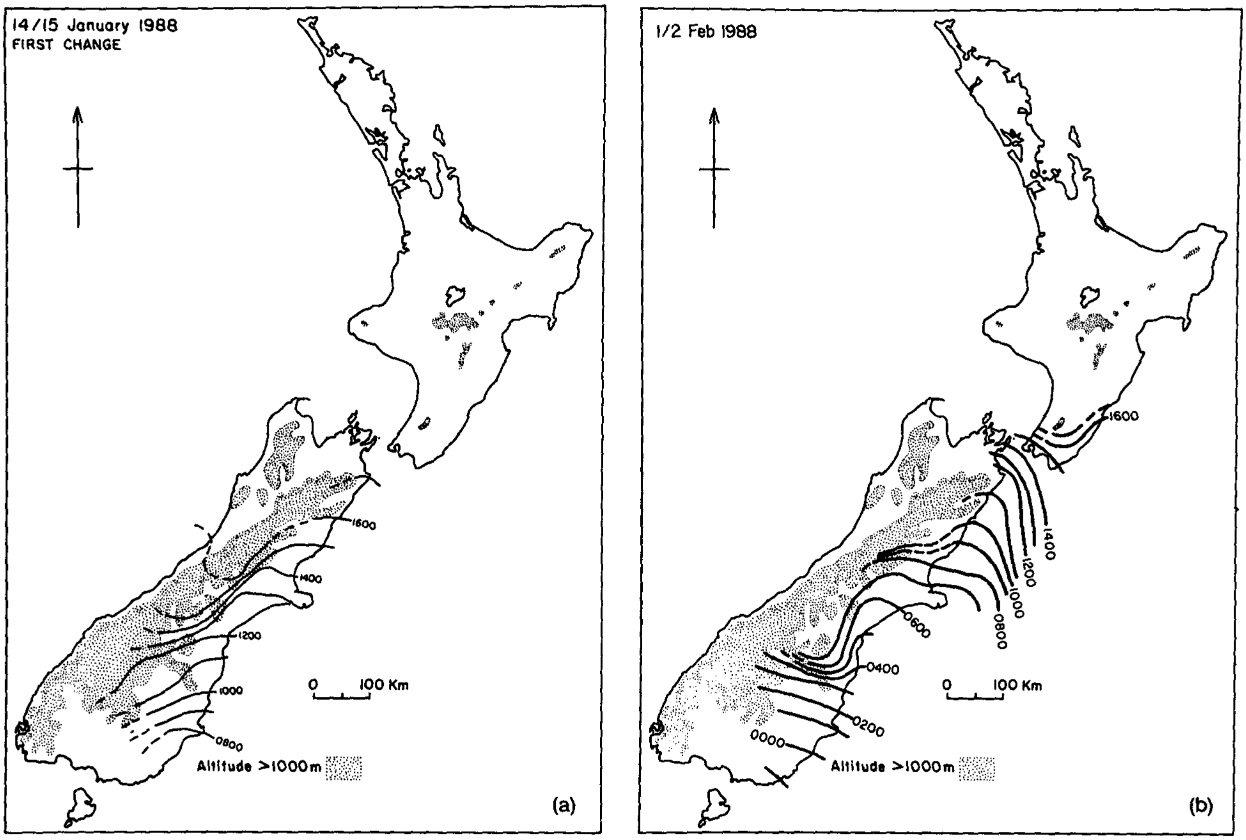


FIG. 21. Isochrones of the position of (a) the first change of event 1: 14 January 1988; and (b) the change of event 5: 2 February 1988.

behind the change, which in all cases was below the mean ridge level (2 km) of the Southern Alps. Not all the fronts had a clear signature at Invercargill. For example, event 1 might have been identified by the strengthening of the wind at 0615 NZDT, by the shift in wind direction shortly before 0800 NZDT, and/or by the rapid decline in θ_e at the surface that occurred at about the same time (Fig. 11b), although θ_e is not normally used routinely by forecasters. Event 2 had no signature at all in the lower atmosphere and the presence of the change was first suspected by the surface wind shift at Oamaru in the late afternoon. In contrast, both events 3 and 5 were recognizable as sharp wind changes at Invercargill; and again, in each case, the wind change heralded a steady decline in θ_e at the surface.

In event 1 a dramatic influence of the cross-mountain flow was evident wherein a marked strengthening

TABLE 1. Information on the relative flow within about 40 km of the southerly changes. The subscripts 1 and 2 indicate the assumptions that the changes moved parallel to the coast (from $\sim$225°) or from the south, respectively. The last column gives the estimated mean wind direction below 600 m following the change for Christchurch and Winchmore for comparison with the assumed direction of movement. The second change of event 1 was not well defined at Winchmore, and no data are available from there for event 3.

	Time (NZDT)		c_1 (m s^{-1})	u'_1 (m s^{-1})	c_2 (m s^{-1})	u'_2 (m s^{-1})	Wind (°)	Wind (°)
	TU	KI					CH	WI
Event 1 No. 1	1200	1600	20.1	20.6	14.6	20.2	200	180
Event 1 No. 2	1640	2100	18.5	8.0*	13.4	10.0*	185	—
Event 2	1550	2320	10.7	7.9	7.7	10.3	185	135
Event 3	2020	0520	8.9	12.7	6.5	8.9	225	—
Event 5	0500	0950	16.6	10.3**	12.0	12.3**	190	150

* These values occurred about 2 h after the change.
** 0730 NZDT sounding.

of the westerly flow at Christchurch above 2 km coincided with a sharp pressure fall and a temporary reversal of the low-level wind about 3.5 h following the change. Unfortunately upper-air data at other stations (i.e., Timaru and Kaikoura) were unavailable on this day to corroborate the association of the strengthening of the westerly wind aloft with the abrupt fall in surface pressure that was observed between Oamaru and Kaikoura. It seems dynamically plausible that the passage of an upper-level jet would be accompanied by a readjustment of the leeside flow and thereby a modulation of the surface pressure wind field. Moreover, this would appear to offer a plausible explanation for the occurrence of the pressure fall that traversed the network (Fig. 14). A similar, but more localized, effect might also provide an explanation for the strong southerly surge that occurred at Kaikoura without a significant fall in temperature or change in surface pressure, almost an hour before the main southerly wind surge and pressure jump.

A likely scenario for the intensification and demise of event 1 is as follows. Following the passage of a Southern Ocean front through Invercargill in the early morning, northwesterly winds crossing the mountains to the north descended over the Canterbury Plains and warmed adiabatically. This warming of an already relatively warm air mass, enhanced by diabatic heating, led to high temperatures over the Plains, thereby increasing the temperature difference across the approaching front. Accordingly, the ageostrophic imbalance of forces across the front, already accentuated by the blocking effect of the Southern Alps on the prefrontal (alongfront) flow, was further strengthened. As a result the cold air accelerated rapidly along the Plains as an unsteady gravity-current-type surge. As the surge advanced, it outran the region where the larger-scale frontogenetic action was concentrated, and the cold air supply to it could not be maintained. As it ran into relatively cool maritime air to the north of Kaikoura and came under the influence of an adverse pressure gradient associated with the airflow patterns in and around the exit to Cook Strait, it steadily decayed. Meanwhile, further to the south, the advance of the upper-level jet led to a restructuring of the cross-mountain flow and to a temporary local reversal of the surface pressure gradient. In turn, this caused a temporary reemergence of a northerly component of near surface flow over the Plains. This enhanced local frontogenesis as the airflow to the south remained southerly. As a result, a second southerly surge was initiated and this *propagated* northwards in association with the larger-scale frontogenetic forcing. The cross-frontal flow behind this change was appreciably less than the speed of the front. This was the change that subsequently crossed the North Island in association with the passage of the upper trough.

Events 3 and 5 differed from event 1 in that the front was oriented more or less meridionally as it approached New Zealand. In neither case was there a discernible passage of an upper-level trough at Christchurch. As in event 1 both were preceded by a northwesterly foehn over Canterbury, but this was not as strong and the prefrontal air mass was not so warm. Moreover, as these events occurred during the evening or early morning, diabatic heating played little or no role in the local frontogenesis. Nevertheless, there was some evidence in each case of a region of positive relative flow behind the change, suggesting that it may have had the local structure of an evolving gravity current.

Event 2 was fundamentally different from the other events in a number of ways. The surface flow was initially southwesterly after the passage of a deep low pressure system across the South Island and there was no warm air mass over New Zealand prior to the change. No surface front was recognizable at Invercargill, and over Canterbury the prefrontal near-surface flow was northeasterly and there was no warm foehn. This event appears to have been initiated by frontogenesis over and east of the South Island in association with a strong westerly jet maximum and a sharpening upper-level trough west of Invercargill (Fig. 8). This was evidenced by the increasing baroclinicity in the 1000–500 hPa thickness field in the subsequent 24 h (not shown) as the upper trough crossed New Zealand. Although this event was associated with a relatively deep airmass change extending to the surface at Christchurch, it seems likely that, at least in the initial stages, the surface feature was largely a result of the development of onshore northeast winds on the east coast of the South Island in response to the developing orographic trough. As the upper trough moved east and surface pressures commenced rising in the south, the winds then returned to a southerly direction, with this windshift gradually organizing itself into a coherent change. By the time it reached Christchurch, there was evidently sufficient difference in the origins of the prechange and postchange air there to produce the observed well-defined airmass change at the surface as well as aloft.

The isochrones of the five[8] wind changes show clearly the tendency for the changes to align themselves parallel with the coast as they move inland (Fig. 21; Sturman et al. 1990), and hence also with the mountains that are themselves approximately parallel with the coast. This can be partly explained as a kinematic effect of the distortion of the approaching fronts by the mountains (e.g., Smith 1985), but it is likely that the temperature gradient normal to the coast plays an important role also. This hypothesis is supported by the numerical study of Reeder (1986), which showed that

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[8] Includes two changes for event 1.

fronts tend to accelerate across a coastline where the land mass is diabatically heated. The isochrones are similar to those for the two southerly busters investigated by Colquhoun et al. (1985; see Figs. 8 and 15), and it seems likely that similar processes are involved. In a detailed numerical study of one of these southerly busters, Howells and Kuo (1988) have shown that a combination of factors are involved in the relatively rapid movement of the change along the coast and just offshore. These include:

(i) channeling of cool maritime air around the southeastern extent of the mountain ranges,
(ii) blocking of the flow on the western side of the mountains,
(iii) adiabatic downslope heating of the prefrontal westerly airflow,
(iv) sensible heating of the prefrontal continental air mass,
(v) reduced frictional coupling of the warm prefrontal westerlies over the cooler ocean, and
(vi) stronger frictional retardation over land to slow the progress of the front.

We may surmise that these conclusions apply equally to the southerly changes we have documented here, but because the mountains are higher in New Zealand and the sensible heating by the land is generally less than over the Australian continent, it would be reasonable to assume some differences in the relative contribution of the foregoing processes between the two countries. Current plans are to carry out a similar study to Howells and Kuo (1988) for the SOUCHEX southerly changes.

The occurrence of shallow frontal-like surges along mountain barriers in other parts of the world is reviewed in a recent paper by Mass and Albright (1987). These authors also document two examples of coastal fronts along the Pacific coast of the United States. They conclude that these are a type of orographically trapped gravity current that is initiated by a reversal of the synoptic-scale pressure gradient along the coastal ranges. The situation in southeastern Australia and New Zealand is different in that the fronts occur in the lee of the orography with respect to the middle-tropospheric flow, rather than on the upwind side as in the cases described by Mass and Albright. However, it is similar to that in the case of a cold-frontal surge along the Pyrenees discussed by Hoinka and Heimann (1988), and one could reasonably surmise that the dynamics of the latter case involved similar processes to the southerly buster and southerly change.

As far as we are aware, the present study of the New Zealand southerly change is the most comprehensive to date and the SOUCHEX experimental data on which the study is largely based are the most detailed that have been so far obtained. We have found evidence that the occurrence and movement of southerly changes along the east coast are controlled largely by synoptic-scale processes through changes in the upper-level winds as a trough approaches in the mean westerly flow. However, adiabatic and diabatic heating, the land–sea temperature contrast, and changes in the mountain wave pattern have an important localized modifying influence. While much has been learned, we are conscious that the data are inadequate to answer many of the questions that have arisen from their analysis. However, we believe that the analysis has provided a basis on which a number of questions concerning the influence of orography on the behavior of cold fronts can be more clearly articulated, thereby providing the impetus for future theoretical and numerical modeling studies.

Acknowledgments. We are grateful to the New Zealand Meteorological Service for providing consumables and staff overtime during SOUCHEX, and base operation facilities at Christchurch. The success of the experiment was assured by the dedication of the staff at the Invercargill, Dunedin, Christchurch, Hokitika, Kaikoura, Kelburn, and Paraparaumu offices; the willing and expert advice of the forecasters at the Christchurch and Wellington Weather Centres; the assistance of Peter Isaacs, Tony Bromley, and Lance Andrews in deploying and operating the acoustic sounder and remote weather stations; and the work of Ingrid Lechner in equipping the F-27 aircraft and processing the data.

We thank also the Monash University team of Max Adams, Anne Becker, Deryn Griffiths, Terry Long, Kathy McInnes, Paul Miesen, Greg Roff, and Wolfgang Ulrich (University of Munich), and personnel of the Geography Department of the University of Canterbury (especially Ian Owens, Martin Single, Kim Dunstan, and Pete Tyree) for their dedicated efforts in tracking balloons and deploying weather stations.

We acknowledge the assistance in New Zealand of the Airways Corporation in making available their F-27 aircraft and for providing facilities at the Oamaru and Timaru airports; the Ministry of Defence for providing the use of a Lake Class naval patrol vessel; the Ministry of Agriculture and Fisheries for siting the acoustic sounder at Winchmore; and the many individuals who allowed equipment to be installed on their land.

We also acknowledge in Australia the CSIRO Division of Atmospheric Research (and particularly Mr. Jimmy Stevenson) for the use of microbarographs and subsequent data processing, and QANTAS airlines for assistance in freighting equipment to New Zealand.

Reduction of data and drafting of diagrams was ably carried out by Linda Sagripanti, Morwenna Griffiths, Jean Sheldon and Louise Hoyle of Monash University; Lesly Coutts and Chris Hayward of the New Zealand Meteorological Service; and Herr H. Wendt of the

University of Munich. Gudrun Fingerle of the University of Munich skillfully typed the manuscript.

Finally, we acknowledge the generous financial support of the New Zealand Meteorological Service, the New Zealand University Grants Committee, the Geophysical Fluid Dynamics Laboratory of Monash University, and the Australian Research Council.

REFERENCES

Cherry, N. J., 1972: Winds and lee waves over Canterbury, New Zealand. *N. Z. J. Sci.*, **15**, 587–600.

Colquhoun, J. R., D. J. Shepherd, C. E. Coulman, R. K. Smith and K. McInnes, 1985: The southerly burster of south eastern Australia: An orographically forced cold front. *Mon. Wea. Rev.*, **113**, 2090–2107.

Coulman, C. E., J. R. Colquhoun, R. K. Smith and K. McInnes, 1985: Orographically forced cold fronts—mean structure and motion. *Bound.-Layer Meteor.*, **32**, 57–83.

Coulter, J. D., 1975: The climate. *Biogeography and Ecology in New Zealand.* G. Kuschel, Ed., The Hague, 689 pp.

Crawford, J. P., 1977: High temperatures in Canterbury, Marlborough, and Hawkes Bay 7 February 1973. New Zealand Meteorological Service Technical Information Circular 159. (Available from New Zealand Meteorological Service, P.O. Box 722, Wellington.)

Crutcher, H. L., R. L. Jenne, J. J. Taljaard and H. van Loon, 1971: Climate of the upper air: Southern Hemisphere. Vol. 4, Selected meridional cross sections of temperature, dew point and height. Navair 50-1C-58. [Available from National Climatic Center, Federal Building, Asheville, N.C., USA 28801.]

de Lisle, J. F., 1965: Extreme surface winds over New Zealand. *N. Z. J. Sci.*, **8**, 422–430.

Farkas, E., 1958: Mountain waves over Banks Peninsula, New Zealand. *N. Z. J. Geol. Geophys.*, **1**, 677–683.

Fitzroy, R., 1863: *The Weather Book: A Manual of Practical Meteorology.* Longman, Green, Longman, Roberts and Green, 463 pp.

Gordon, N. D., 1984: Numerical prediction in New Zealand: Accuracy and impact. *Proc. of the Asia and South West Pacific Tech. Conf. on Operational Weather Forecasting Including Interpretation of Numerical Weather Prediction Output,* Beijing, 100–106. (Also issued as New Zealand Meteorological Service, Scientific Rep. No. 1.)

Hill, H. W., 1969: A synoptic study of a large-scale meridional trough in the Tasman Sea–New Zealand area. *N. Z. J. Sci.*, **12**, 576–593.

——, 1980: A case of intense cyclogenesis in the Tasman Sea. *N. Z. J. Sci.*, **23**, 111–127.

Hoinka, K.-P., and D. Heimann, 1988: Orographic channeling of a cold front by the Pyrenees. *Mon. Wea. Rev.*, **116**, 1817–1823.

Howells, P. A. C., and Y-H. Kuo, 1988: A numerical study of the mesoscale environment of a southerly buster event. *Mon. Wea. Rev.*, **116**, 1171–1788.

Hutchings, J. W., 1944: Orographic disturbances of the pressure field over New Zealand. New Zealand Meteorological Service Miscellaneous Meteorological Notes, Series A, No. 7. (Available from New Zealand Meteorological Service, P.O. Box 722, Wellington.)

Lee, T. J., R. A. Pielke, R. C. Kessler and J. Weaver, 1989: Influence of cold pools downstream of mountain barriers on downslope winds and flushing. *Mon. Wea. Rev.*, **117**, 2041–2058.

McGann, R. P., 1983: The climate of Christchurch. New Zealand Meteorological Service, Miscellaneous Publication 167(2), 27 pp. (Available from New Zealand Meteorological Service, P.O. Box 722, Wellington.)

McKendry, I. G., 1983: Spatial and temporal aspects of the surface wind regime on the Canterbury Plains, New Zealand. *J. Climatol.*, **3**, 155–166.

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

Mass, C. F., and M. D. Albright, 1987: Coastal southerlies and alongshore surges of the West Coast of North America: Evidence of mesoscale topographically trapped response to synoptic forcing. *Mon. Wea. Rev.*, **115**, 1707–1738.

Reeder, M. J., 1986: The interaction of a surface cold front with a prefrontal thermodynamically well-mixed boundary layer. *Aust. Meteor. Mag.*, **34**, 137–148.

Revell, C. G., M. Pascoe and S. J. Reid, 1987. East coast southerly changes. New Zealand Meteorological Service Scientific Rep. 27, 40 pp. (Available from New Zealand Meteorological Service, P.O. Box 722, Wellington.)

Ridley, R. N., 1987: A climatology of southerly changes at Christchurch. New Zealand Meteorological Service Scientific Rep. 28, 16 pp. (Available from New Zealand Meteorological Service, P.O. Box 722, Wellington.)

——, 1990: Southerly buster events in New Zealand. *Weather and Climate,* (in press).

——, M. A. Page, R. K. Smith, T. S. Steiner and A. P. Sturman, 1991: The New Zealand Southerly Change Experiment (SOUCHEX). Centre for Dynamical Met. Tech. Rep. No. 1. Monash University, Melbourne, (Available from: Centre for Dynamical Meteorology, Monash University, Clayton, Vic. 3168, Australia.)

Ryan, A. P., 1987: The climate and weather of Canterbury. New Zealand Meteorological Service, Miscellaneous Publication 115(7), 66 pp. (Available from New Zealand Meteorological Service, P.O. Box 722, Wellington.)

Smith, R. B., 1982: Synoptic observations and theory of orographically disturbed wind and pressure. *J. Atmos. Sci.*, **39**, 60–70.

Smith, R. K., and M. J. Reeder, 1988: On the movement and low-level structure of cold fronts. *Mon. Wea. Rev.*, **116**, 1927–1944.

Stainer, B. A., 1983: The distribution of wind and pressure in Cook Strait in strong northerlies. *Mar. Obs.*, **53**, 77–84.

Steiner, J. T., C. G. Revell, R. N. Ridley, R. K. Smith, M. A. Page, K. L. McInnes and A. P. Sturman, 1987: The New Zealand Southerly Change Experiment. *Bull. Amer. Meteor. Soc.*, **68**, 1226–1229.

Sturman, A. P., R. K. Smith, M. A. Page, R. N. Ridley and J. T. Steiner, 1990: Mesoscale surface wind changes associated with the passage of cold fronts along the eastern side of the Southern Alps, New Zealand. *Meteor. Atmos. Phys.*, **42**, 113–143.

Trenberth, K., 1977: Surface atmospheric tides in New Zealand. *N. Z. J. Sci.*, **20**, 339–356.