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A Study of Interacting Multi-Scale Wind Systems, Canterbury Plains, New Zealand

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With 11 Figures

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Summary

The wind regime of the Canterbury region, New Zealand, is composed of several interacting multi-scale wind systems all of which show strong diurnal periodicity. The dynamic orographic effect of the Southern Alps on the prevailing westerly flow results in perturbations to the pressure field and localized antitriptic airflow. Superimposed on this larger scale process are thermotopographic effects resulting from both regional and local land-sea thermal contrasts and slope heating. These processes act within an hierarchy of scales to produce a complex wind regime characterized by marked temporal variability, a layered vertical structure and the frequent occurrence of convergence lines and shear zones. The synergistic nature of the forcing mechanisms and the tendency for nocturnal decoupling of the boundary layer due to stability variations makes it difficult to differentiate and label discrete wind components.

Attempts to simulate this regime using the Colorado State University mesoscale model showed that the model was unable to adequately resolve both the dynamic orographic effect and the local thermotopographic effect because of their differing scales of influence. These results suggest that a more holistic approach to both empirical and theoretical studies in such environments is required if more accurate wind field forecasting is to be achieved.

Zusammenfassung

Eine Studie zusammenwirkender Windsysteme verschiedener Größenordnungen, Canterbury Plains, Neuseeland

Das Windregime des Gebiets von Canterbury, Neuseeland, setzt sich aus verschiedenen zusammenwirkenden Windsystemen verschiedener Größenordnungen zusammen, die alle einen starken Tagesgang aufweisen. Der dynamisch-orographische Effekt der neuseeländischen Alpen auf die vorherrschende Westströmung führt zu Störungen im Druckfeld und lokalen Luftbewegungen im Lee. Diesem großräumigen Prozeß sind thermisch-topographische Effekte überlagert, die sowohl durch regionale als auch lokale thermische Unterschiede zwischen Land und Meer und die Erwärmung der Hangregion hervorgerufen werden. Die Vorgänge spielen sich in einer Hierarchie von Größenordnungen ab. Sie erzeugen ein kompliziertes Windsystem, das durch hohe zeitliche Variabilität, eine schichtweise thermische Struktur und häufige Konvergenz- und Scherungszonen gekennzeichnet ist. Die synergetische Natur der Antriebe und die Tendenz zum nächtlichen Entkoppeln der planetaren Grenzschicht aufgrund von Stabilitätsschwankungen macht es schwer, die einzelnen Windkomponenten zu trennen und zuzuordnen.

Die Versuche, dieses Regime mit Hilfe des Mesoscale-Modells der Colorado State University zu simulieren, zeigten, daß es aufgrund der verschiedenen Größenordnungen des Einflusses nicht geeignet war, gleichzeitig den dynamisch-orographischen und den thermo-topographischen Effekt zu reproduzieren. Diese Ergebnisse legen sowohl für empirische wie für theoretische Untersuchungen einen holistischeren Ansatz nahe, um eine genauere Prognose des Windfeldes zu ermöglichen.

1. Introduction

The study of regional and local airflow patterns has gained increasing popularity for both applied and theoretical reasons. "Local" is used here to represent a characteristic horizontal distance of approximately 10–100 km, "regional" 100–500 km and "synoptic" 500–5000 km (similar to Barry and Perry 1973). From the applied point of view, an understanding of airflow at such scales is seen as important in atmospheric dispersion studies, where concern is being broadened from a focus on single stack and city-wide pollution to regional diffusion (for example, of radioactive material). It is also apparent that many of the models used to predict pollution concentrations are wildly inaccurate in areas dominated by complex local airflow regimes (Misra and McMillan 1980; McRae et al. 1981; Sturman 1985). These regimes have an impact on many other aspects of mankind's activities, including aerial crop spraying, insect dispersion, civil aviation, severe storm development, and recreation. However, until recently most research of regional and local airflow has concentrated on individual components, such as land and sea breezes or mountain and valley winds, without examining the way in which components of differing strength and scale interact (Clements and Nappo 1983; Gutman 1983; Keen and Lyons 1983; Manins and Sawford 1979; Simpson et al. 1977). A change in approach appears to have been stimulated by the development and application of mesoscale atmospheric circulation models. Given sufficient computing power, such models should allow the simulation of airflow over a region influenced by a range of processes operating at differing scales (Fosberg et al. 1976; Pielke 1984; Schlunzen and Schatzmann 1984). However, most simulations to date have concentrated on the study of particular processes (Huss and Feliks 1981; Physik 1976, 1980; Pielke 1974). Such studies are useful in isolating and examining components of airflow regimes, but are unable to explain anomalous features which result from interacting forcing functions.

There are several types of forcing function influencing airflow at the scales examined here. Firstly, there is the synoptic scale airflow which may be modified by topography. Secondly, there is the orographic effect of mountain barriers producing pressure field perturbations as well as airflow modification. The orographic effect is both mechanical and thermodynamic. Thirdly, there are thermotopographic effects which may operate at different scales. For example, slope winds develop due to slope heating and cooling, while land and sea breezes result from differential heating and cooling of land and sea surfaces.

This paper aims to:

1) Show the importance of taking an holistic view in examining regional and local airflow regimes and the factors that influence them. Such a view is particularly important for accurate wind field forecasting.

2) Examine and explain apparent differences between observation and classical ideas of such airflow regimes in light of both field research and numerical modelling.

3) Provide a basis for more detailed analysis of specific aspects of local and regional airflow patterns, with the ultimate objective of improving knowledge of the physical processes involved and subsequently our forecasting ability.

Previous studies (McKendry 1983; Ryan 1980; Sturman and McKendry 1984; Sturman and Tyson 1981) suggest that the Canterbury Plains is an ideal location for investigating the effect of processes acting at different scales on wind regimes.

2. Regional Airflow Background

Airflow over the South Island of New Zealand is dominated at the synoptic scale by the interaction of high alpine topography (frequently exceeding 3000 m in altitude) with the strong westerlies of this latitude zone. These westerlies lie between the band of slow-moving sub-tropical anticyclones to the north and cyclonic disturbances which move more quickly from west to east over the ocean between New Zealand and Antarctica (Maunder 1971; Sturman et al. 1984). In spite of the strength and persistence of westerly flow in this region, the surface wind field illustrates clearly the extent of topographic modification (Fig. 1). Major surface wind directions either side of the Southern Alps show a northwest-northeast orientation, parallel to the mountain axis. It is apparent from earlier research that northeasterlies frequently occur on both sides of the mountains in opposition to synoptic westerly flow (McKendry 1983; Neale and Thompson 1978; Sturman and Tyson 1981). The vertical dimension is less well known because of limited data. However, study so far has shown that westerly winds continue aloft frequently disconnected from surface airflow which may extend from a few hundred to two to three (Ryan 1980; Sturman and McKendry 1984; Sturman and Tyson 1981) thousand meters.

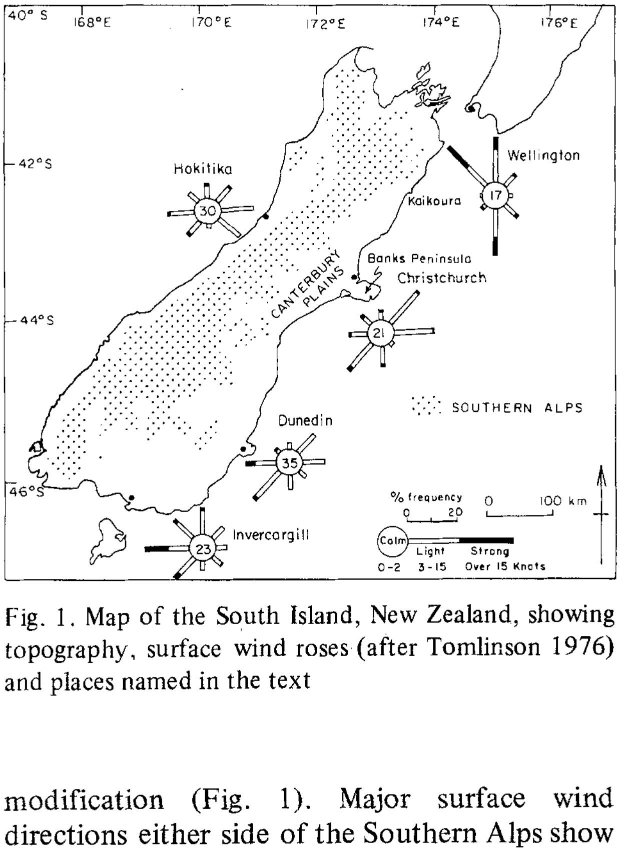

Fig. 1. Map of the South Island, New Zealand, showing topography, surface wind roses (after Tomlinson 1976) and places named in the text

The limited north-south extent of the Southern Alps is a major factor in the resulting complex wind regime, causing significant differences from the effects of other north-south barriers such as the Rockies and Southern Andes. The classic perturbation of the surface pressure field occurs with the development of high pressure to windward and low pressure to the lee (de Lisle 1969; Hill 1979; Smith 1982). However, in contrast to basic theory, the sub-synoptic scale flow produces a cross-isobaric wind normal to the orographic barrier, rather than curved flow following the distorted isobars. Thus the airflow at this scale conforms to Le Chatellier's principle which recognizes that because of inherent inertia in the strong westerly current, the wind is unable to adapt to the new pressure pattern generated by the mountains.

The airflow pattern created through orographic deformation is three dimensionally more complex than the present instrumental networks allows us to observe in detail. However, it is apparent from available data that there are both upstream and downstream effects. It is clear, for example, that westerlies arriving on the upstream side of the barrier anticipate the obstruction and may start to rise up to perhaps 100 km before reaching the mountains (Neale and Thompson 1978). A region of slack air may be trapped immediately upwind of the mountains or flow parallel to the alpine axis (Fig. 2). That which flows parallel to the mountains may travel around the ends of the barrier. This splitting of the lower layers of the air current has also been noted on the windward side of the European Alps (Pierrehumbert and Wyman 1985). The airflow around the northern end is concentrated by passage through Cook Strait and subsequently results in northeasterly winds along the east coast of the South Island due to convergence onto the orographically-induced lee trough (de Lisle 1969). This northeasterly frequently extends almost all the way down the east coast undercutting the foehn wind over the Canterbury Plains (Sturman and Tyson 1981).

The interaction of synoptic scale flow with the Southern Alps therefore creates a three dimensionally complex airflow regime frequently exhibiting rapid changes which are often difficult to forecast. The addition of a diurnally-varying airflow component makes the situation yet more complex. However, recent and current research has improved our knowledge of the sub-synoptic processes operating and our ability

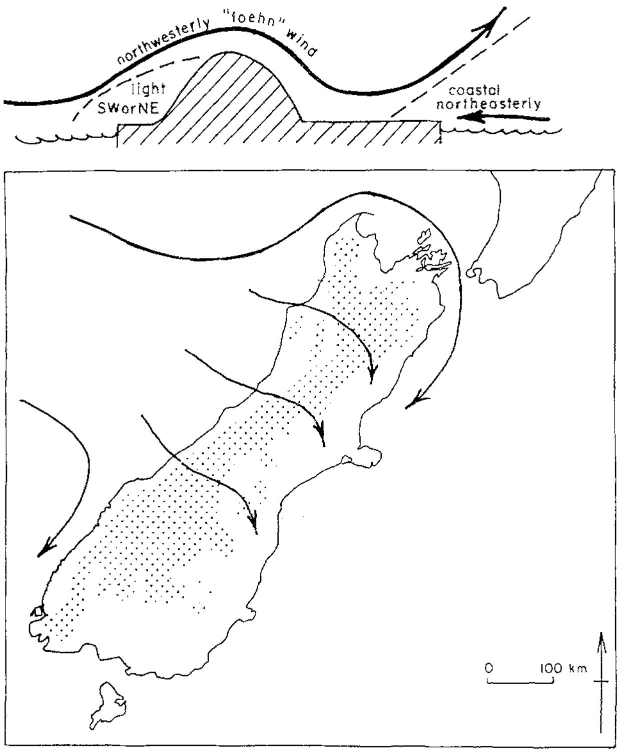

Fig. 2. Schematic illustration of mesoscale airflow features over the South Island

to provide local forecasts (Sturman and McKendry 1984; Sturman and Tyson 1981; Trenberth 1977). Further results of this continuing research are examined in the following sections.

3. Synoptic and Regional Scale Processes

Trenberth (1977) identified strong atmospheric tides in New Zealand's surface pressure field and suggested that the major cause of the diurnal solar tide was the interaction of the mountainous terrain with synoptic scale circulation. The pressure pattern deformation produced by the mountains appeared to be greatest in early afternoon and at a minimum at night. Because of seasonal variations in the synoptic scale circulation, maximum amplitude occurs in November when westerly flow is most dominant. Trenberth (1977) also suggested that relative differences in phase and amplitude of the atmospheric tide are caused through modification of the orographic distortion by heat low effects associated with diurnal heating, which

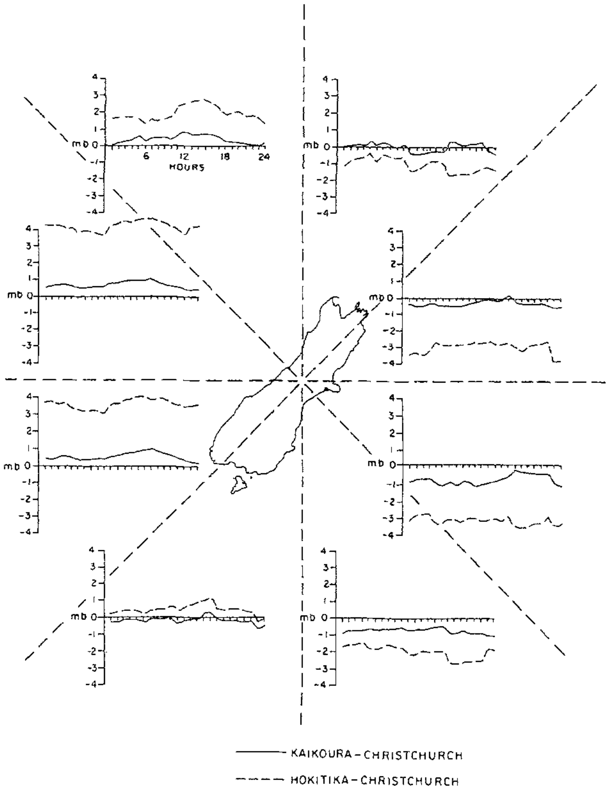

Fig. 3. Diurnal variation of pressure differences for eight 600 mb wind directions (delineated by dashed lines) at Christchurch Airport 1 January 1982 to 31 August 1983

are therefore greatest in the afternoon and summer.

The influence of synoptic airflow direction on these atmospheric tides is examined here and illustrated in Fig. 3. Pressure differences Kaikoura minus Christchurch, and Hokitika minus Christchurch are used to indicate spatial and temporal variations in the pressure field over Canterbury. Synoptic airflow is represented by 600 mb directions for Christchurch Airport. It is apparent that westerly flow produces not only a strong trans-alpine pressure gradient (Hokitika-Christchurch), but also a gradient along the lee side between Kaikoura and Christchurch. The resulting anti-triptic flow converges on the Canterbury area. These gradients are reversed under easterly and southeasterly synoptic flow. The diurnal periodicity in pressure gradients associated with synoptic westerly flow noted by Trenberth (1977) is evident in Fig. 3, and contributes to an enhanced "sea breeze" along the coast of north Canterbury with maximum

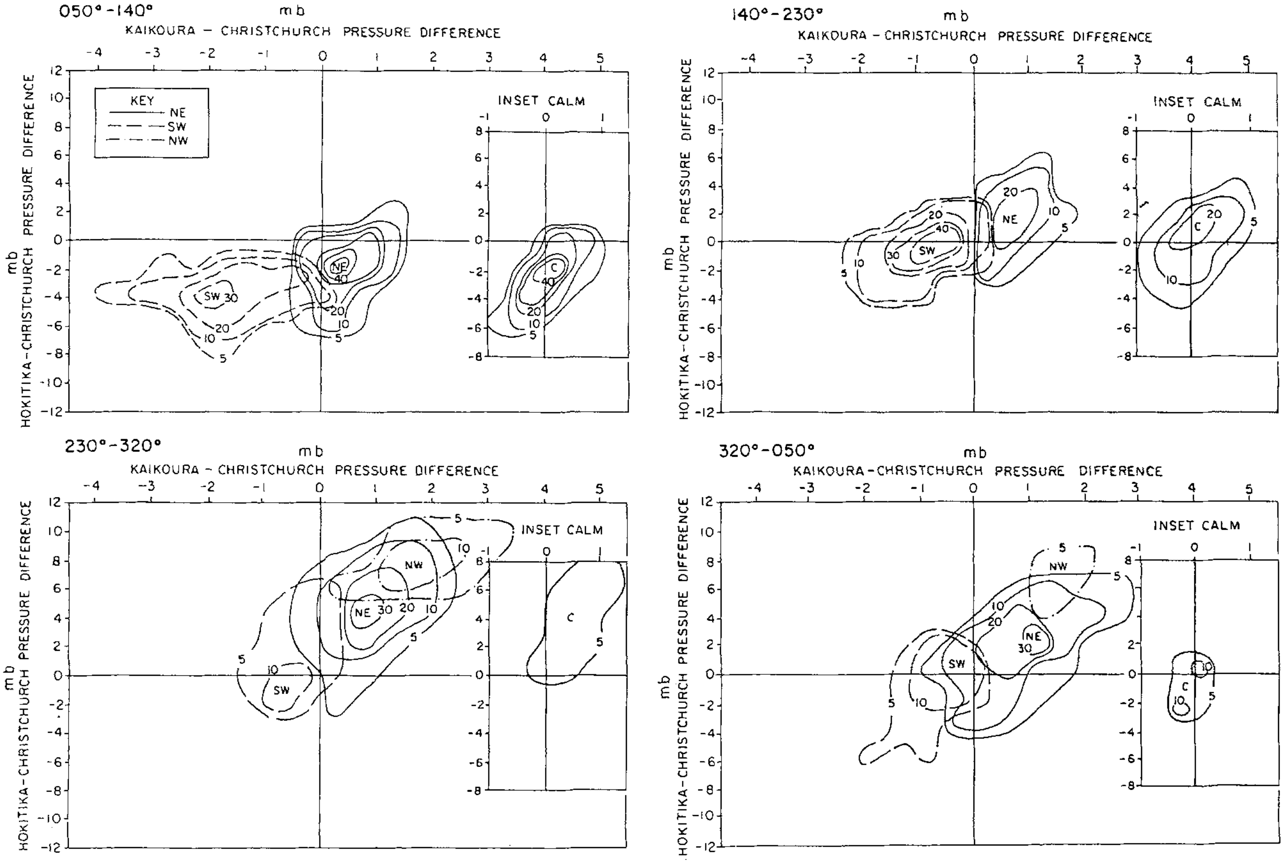

Fig. 4. Frequency of hourly surface winds at Christchurch Airport by pressure differences for four 600 mb wind direction classes, 1 January 1982 to 31 August 1983 (contours represent frequency per thousand for each class)

wind speeds in the afternoon (Sturman and Tyson 1981).

The influence on surface airflow is shown by Fig. 4 in which hourly surface wind frequencies at Christchurch Airport are related to the Kaikoura-Christchurch and Hokitika-Christchurch pressure differences for four 600 mb flow directions. The most conspicuous feature of the surface wind in this part of the Canterbury Plains is the strong tendency for winds parallel to the mountains irrespective of the 600 mb flow direction as evident in Fig. 4. Even with easterly synoptic flow the barrier effect of the Southern Alps results in a high proportion of southwesterly surface winds. It is apparent that the direction of airflow along the eastern side of the mountains is strongly dependent on the Kaikoura-Christchurch pressure differences. However, in examining the occurrence of northeasterly winds at Christchurch, it is apparent that some synoptic flow directions provide preferential conditions. Fig. 5 shows the relationship between surface gradient wind direction, lee trough development and northeasterly winds at 1500 h local time (the time of Trenberth's diurnal maximum in lee trough development). It is apparent that although southwesterly gradient flow was most frequent during the study period, lee trough and northeasterly development is most often associated with northwesterly gradient flow perpendicular to the Southern Alps.

4. Local Thermotopographic Influences

The largely dynamic regional effects described above interact strongly with local thermotopographic influences to create Canterbury's complex mesoscale wind regime. These thermotopographic influences are largely due to the temperature difference between land and sea, but may also be due to slope heating on the alpine foothills (Sturman and McKendry 1984).

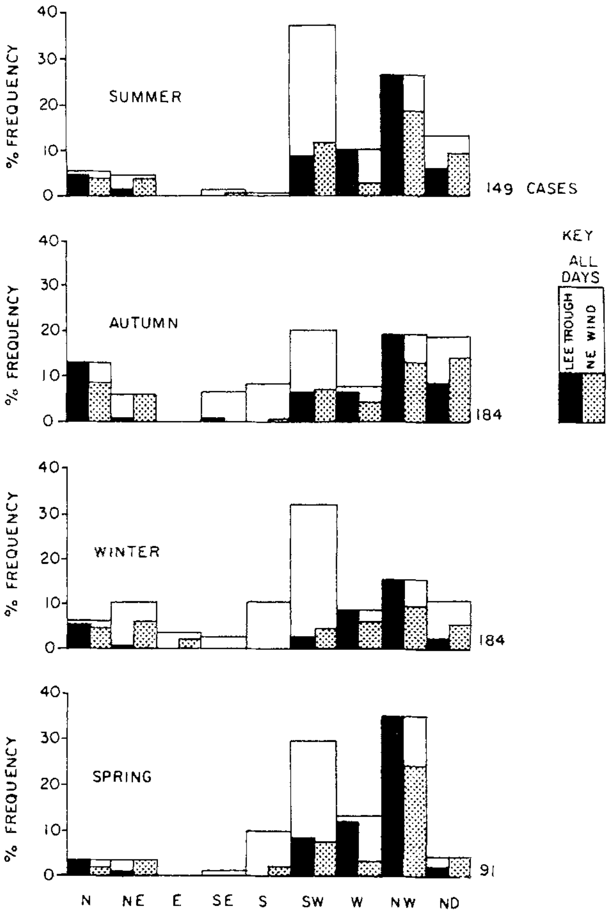

Fig. 5. Frequencies of gradient wind direction classes, lee trough development and northeasterly winds at Christchurch Airport at 1500 hr local time (1 January 1982 to 3 August 1983)

Fig. 6 shows that it is difficult to separate out the sea breeze component from the lee trough and other influences. It is clear that northeasterly winds initiated in the morning tend not to be associated with the expected land-sea temperature gradient. Northeasterlies initiated in the afternoon are more typical of the classical sea breeze but still only 65.3% are associated with positive differentials. Thus, the onshore airflow north of Banks Peninsula is largely due to the orographic effect of the Southern Alps, though the diurnal variation in wind strength noted in previous studies (e.g. Sturman and Tyson 1981) is assisted by the land-sea temperature differentials.

Similarly, the occurrence of northeasterly airflow is uniform throughout the year while the number of hours of this flow direction shows a distinct seasonal variation (Fig. 7). This

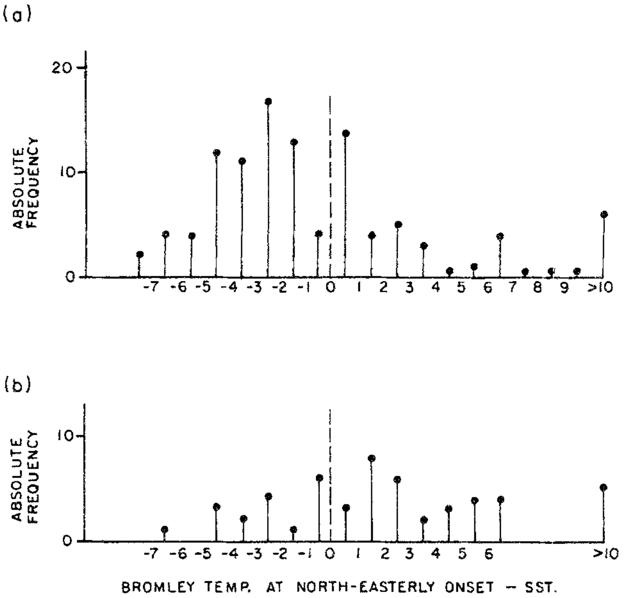

Fig. 6. Frequency of land-sea temperature differences at onset of surface northeasterlies at Bromley (26 August 1982 to 31 August 1983) for: a) northeasterlies initiated between sunrise and midday (104 cases), b) northeasterlies initiated between midday and sunset (52 cases)

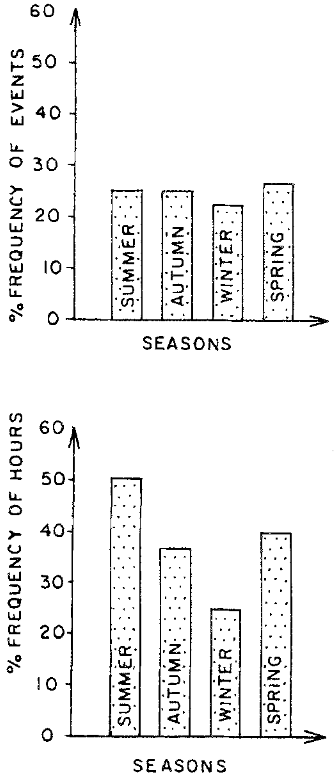

Fig. 7. Percentage frequency of total surface northeasterly episodes by season, and percentage of total hours in each season associated with northeasterly surface flow at Christchurch Airport (1133 cases, 1 April 1967 to 31 March 1972)

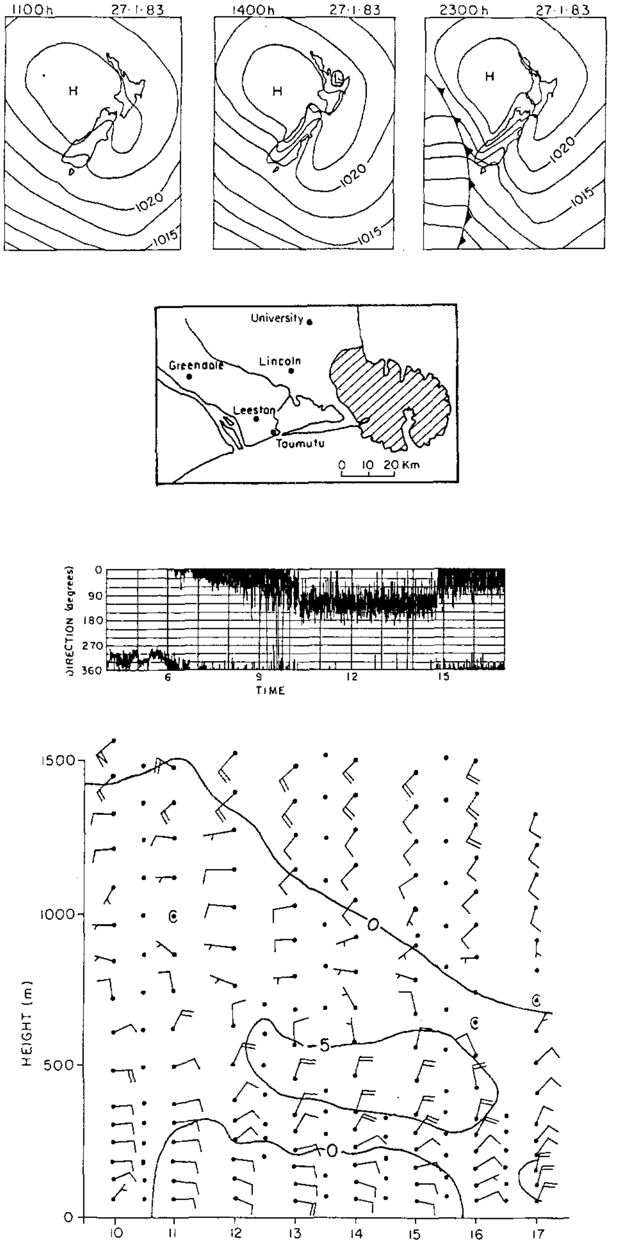

Fig. 8. Example of southeasterly sea breeze, 27 January 1983. a) Surface synoptic isobaric maps, b) location map, c) wind direction trace, d) height-time cross-section of onshore component at Taumutu

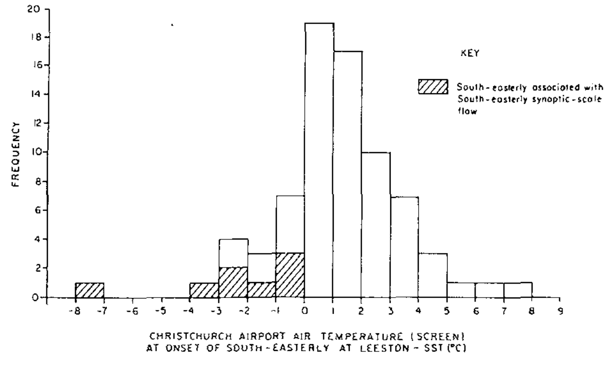

Fig. 9. Frequency of land-sea temperature differentials for southeasterlies embedded in northeasterlies at Leeston

relates to the daily heating and cooling cycle and the effect on the surface wind environment of diurnal stability variations. Increased stability at night results in the decoupling of the prevailing daytime wind from the surface. The stably stratified boundary layer is frequently associated with drainage flow which follows the sloping terrain (Ryan 1980). The result is an apparent nocturnal land breeze. This illustrates a fault in the traditional theory of local winds, in attempting to separate out and label discrete wind components. This approach is mirrored in texts such as Atkinson (1981) where separate chapters deal with each component. It is difficult, however, for them to be differentiated in the real world. For example, the diurnal stability cycle frequently produces a surface wind reversal over Canterbury identical to that produced by the classical land and sea breeze system.

The regional airflow regime is made more complex by the differing orientation of the coastline north and south of Banks Peninsula. The diurnally-varying sea breeze component is more clearly discernible south of the peninsula where it is not masked by lee trough-induced onshore flow. Fig. 8 provides an example of the change in surface wind direction associated with the southeasterly sea breeze embedded in a northeasterly flow at Leeston. In the example shown, the sea breeze can be differentiated from the low level north-easterly by the characteristic abrupt shift in surface wind direction from north-easterly to south-easterly between 1000 and 1500 h. In the vertical profile, the sea breeze appears as a layer of onshore flow (positive onshore component) up to 300 m in depth while immediately aloft there is a marked strengthening of north-north-easterly flow suggesting the presence of return flow. Above the north-easterly the flow is westerly to southwesterly. These localized southeasterly sea breezes follow the classical model and are a summer daytime phenomenon associated with positive land-sea temperature differentials (Fig. 9). However, when associated with the

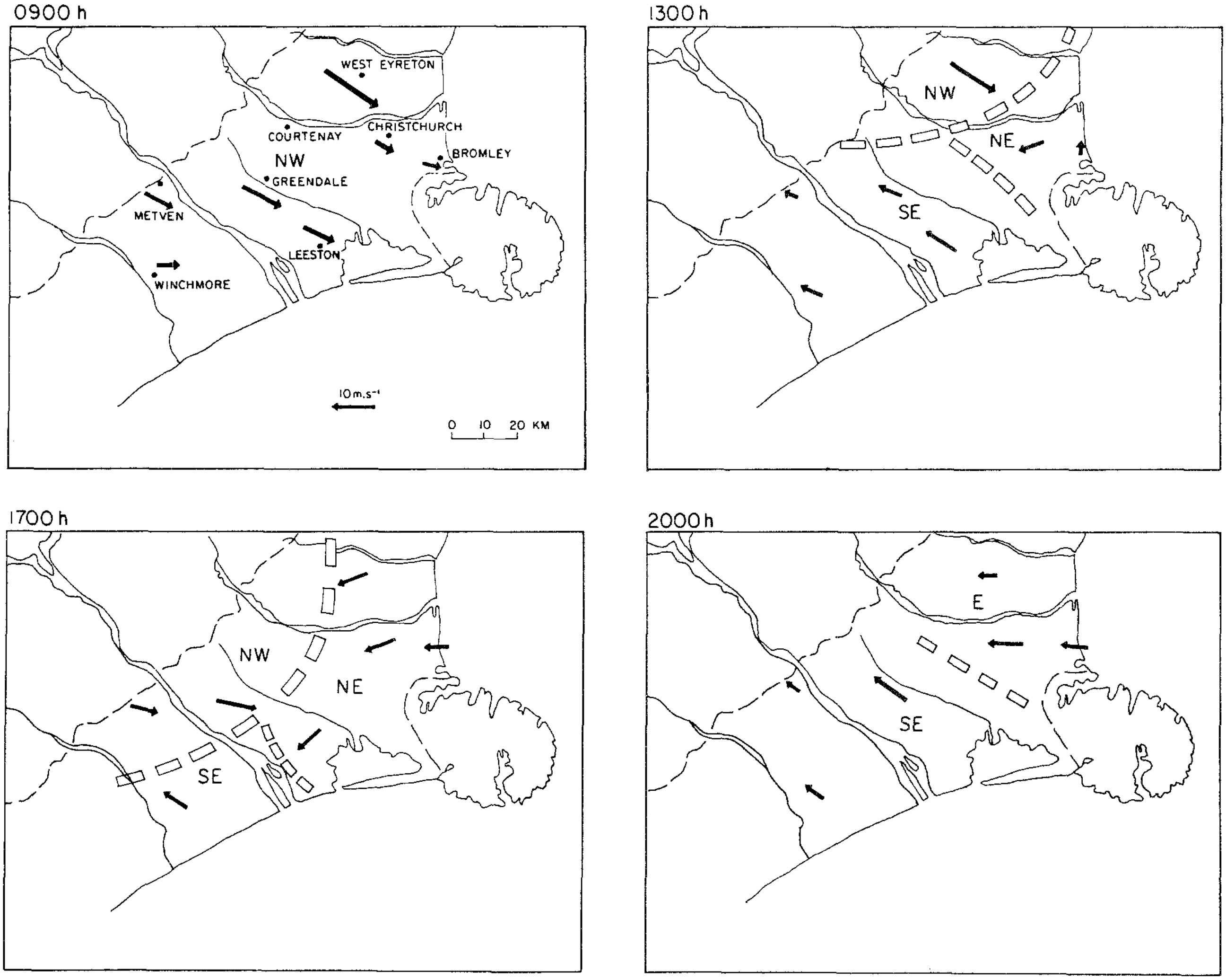

Fig. 10. Spatial and temporal variations in surface airflow over the Canterbury Plains on 4 February 1983

development of an orographic lee trough, the sea breeze southeasterly at Leeston may be obliterated when the northeasterly increases in strength or its momentum is transferred downwards because of increased convective instability (as shown in Fig. 8 from 1540 h). Although the southeasterly is thermally driven, it is dependent on variation in the strength of the lee trough. As a result, it is as difficult to predict as the northeasterly north of the peninsula.

5. Discussion

In examining the local airflow regime of the Canterbury Plains, it has become increasingly apparent that the region provides a unique opportunity to examine the interaction of forces which operate at several scales to produce a complex wind environment. In many parts of the world, the separate local wind components are most easily distinguishable. For example, the sea breezes of Florida are largely unmodified by other local wind processes because of the simple topography. The southern hemisphere mid-latitude location of the South Island, together with its terrain, results in at least three mechanisms which complicate the local wind regime. The dynamic orographic effect of the Southern Alps on the prevailing westerly windfield is a major feature, resulting in perturbations of the pressure field and localized anti-triptic airflow. The thermotopographic effects of the land-sea temperature difference and slope heating and cooling play an important role, while diurnal stability variations produce wind changes in the boundary layer which can confuse the picture. In particular, these stability variations can produce diurnal reversals of airflow expected of a true land-sea breeze system.

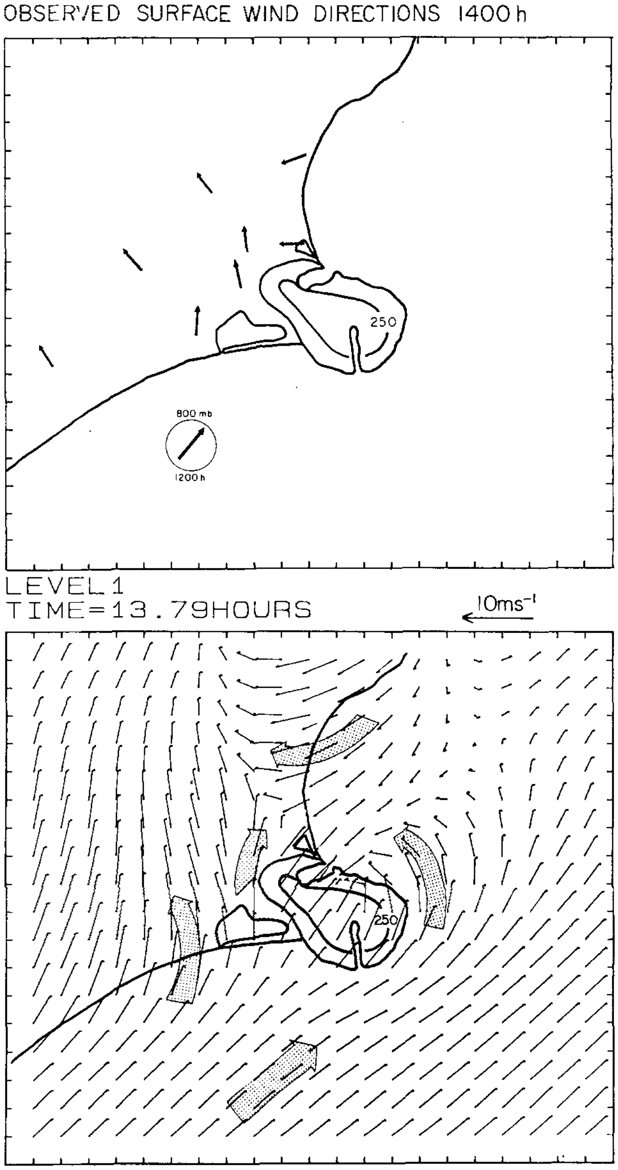

Fig. 11. Predicted and observed airflow at 1400 hr 10 February 1983, based on summer simulation for southwesterly gradient flow

This complexity makes local weather forecasting more difficult than in a situation where a single mechanism is dominant. It is apparent that airflow over Canterbury varies temporally and spatially, so that at any point in time up to three different surface wind directions may be observed over the area. As the forcing functions vary so the dominance of particular wind directions changes. Fig. 10 provides an example of the typical spatial and temporal variations in surface airflow which may occur across the plains throughout the year. Pressure differences along the lee side of the Southern Alps are used operationally to forecast the occurrence of southwesterly and northeasterly winds (as indicated by Fig. 4). However, slight changes in the gradient wind direction and its interaction with the mountain barrier result in rapid wind direction reversals. The airflow structure is therefore three-dimensionally complex including convergence lines and shear zones between differing air currents, which may lead to cloud and thunderstorm development.

The Colorado State University three-dimensional mesoscale numerical model (Mahrer and Pielke 1977, 1978; Pielke 1974; Pielke and Mahrer 1978) has been applied to the investigation of thermo-topographic forcing over the Canterbury Plains region (McKendry 1985). Results agree closely with observations for situations in which the local wind regime is not complicated by the low level north-easterly or foehn north-westerly (Fig. 11). However, in order to adequately represent the various forces mentioned above such simulations should resolve phenomena operating at scales up to and beyond that of the entire South Island (greater than 1000 km in length with terrain rising to 3000 m). Not only did computational constraints prevent such an approach but it is unlikely that current mesoscale models could realistically represent flow at such a scale. It is apparent that as computer power increases and models are improved, it will be possible to examine local wind regimes in a more holistic way and provide more accurate forecasting.

In comparing our results with classical local wind systems, it is frequently difficult to differentiate individual local wind components, such as land or sea breezes. It is also easy to confuse a land breeze and a drainage wind, or a sea breeze and a lee trough wind. There are few studies concerned with a wind environment involving several multi-scale components. An exception is Ryan's (1977) study of local winds in California in which both sea breezes and mountain and valley wind systems are incorporated. However, from a forecasting point of view it is important to take an holistic approach.

The lee trough-induced anti-triptic wind occurring along the east coast of the South Island is a feature not recorded elsewhere to the authors' knowledge, It is quite conceivable that it occurs in other areas, perhaps in the European Alps, but has not been researched. The thermotopographic influences are more predictable, being composed of the broad scale effects of temperature differences in generating land and sea breezes, as well as the smaller scale stability effects and drainage wind development.

6. Conclusion

This paper has examined the major characteristics of a wind regime composed of several interacting multi-scale wind systems. The emphasis of the research is on the interaction of these different wind systems, so that knowledge of the various physical processes and its application to local forecasting can be improved. It is apparent that, although few studies have taken an holistic view of complex wind regimes, such an approach is important for accurate forecasting.

Ultimately, it is hoped that three-dimensional mesoscale models can be enmeshed in regional atmospheric circulation models so that processes operating at different scales can be adequately represented and their effect determined. Although features of the wind regime studies here are unique to Canterbury, they provide useful examples of the effect of interacting forcing functions, and have allowed assessment of the way in which orographic effects can combine with regional and local effects to produce a unique wind environment.

Acknowledgements

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