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Synoptic and sub-synoptic circulation effects on wind resource variability — A case study from a coastal terrain setting in New Zealand

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This paper investigates linkages between synoptic and sub-synoptic scale atmospheric circulation and temporal wind resource variability, adopting a synoptic weather typing approach. These linkages were examined in a complex terrain, coastal setting in southern New Zealand. Over a 28 month period, approximately 71% of the intermonthly variability in power density was explained by the monthly frequency of a subset of weather types. Within this subset, weather types associated with strong southwest or west orientated pressure gradients were related to enhanced power density, whereas weather types associated with stagnant pressure gradients were related to reduced power density. At the sub-synoptic scale, the effect of the sea breeze on the wind resource was found to be of importance but dependent on both the season and the ambient larger scale atmospheric circulation. Aspects of the sea breeze circulation also appear to be complicated by additional thermal and dynamical influences associated with the larger scale terrain complexity. Similar wind regimes likely occur elsewhere and should be examined specifically in the context of the wind resource.

1. Introduction

Despite rapid and global growth in installed wind energy capacity over the last decade (e.g. Ref. [30]), a practical challenge for the wind energy industry remains related to the stochastic and intermittent nature of wind, which can make generation difficult to forecast over a range of time scales or impose supply-demand issues and additional costs [20,40]. The characteristics of time varying wind speed records at heights in the atmosphere relevant to wind turbines are strongly influenced by various atmospheric and climatic phenomena over a range of space-time scales. Therefore, establishing direct and quantifiable linkages between the temporal variability in the wind regime and multi-scale atmospheric and climatic phenomena can enable a more comprehensive assessment of the feasibility of electricity generation from wind energy at a particular site. Establishing such linkages is also important in the context of how supply from other renewables (such as hydroelectric) are sensitive to atmospheric circulation and climate variability [42]. For example, 'moderate' strength correlations (rank correlation coefficients up to 0.5) have been reported between wind generation and hydro inflows for some regions of New Zealand [9], with further research needed to examine climatic influences on supply variability across a range of renewable sources.

Owing to the mid-latitudinal position of New Zealand (spanning 34 to 47°S), the weather and climate is strongly influenced by two prominent features of the southern hemispheric atmospheric circulation. These include a band of subtropical anticyclones that generally lies to the north of New Zealand, and a westerly wind belt that generally lies to the south of New Zealand [51]. The latitudinal position and extent of these circulation features shift seasonally, influencing many aspects of New Zealand's climate, including near surface wind speed. The subtropical anticyclones tend to be situated further north in winter (June to August) and further south in summer (December to February). The westerly wind belt is often enhanced in spring (September to November) as the subtropical anticyclones begin to migrate southward and pressure gradients are enhanced (more tightly constrained) over much of New Zealand; subsequently strong westerly wind speeds are often most frequent in spring [49]. The large land mass of the Australian

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continent also acts to amplify seasonal variation in the synoptic scale atmospheric circulation over New Zealand, with thermal low pressure development in the interior of the Australian continent in spring strengthening the westerly belt over southern New Zealand [17]. These features of the synoptic scale circulation in the atmosphere, relevant to the New Zealand region, can be represented in synoptic weather typing approaches on daily time scales (e.g. Refs. [26,27]).

In New Zealand, the link between geostrophic and near surface winds is often complicated by regional scale considerations including terrain complexity and proximity to the ocean. Notably, the orographic influence of the Southern Alps (shown in Fig. 1) acts to disrupt the predominant westerly flow over the South Island. When airflow is directed over the Southern Alps, this disruption leads to a warm and gusty north-westerly foehn wind in the lee of the Southern Alps [29]. When airflow is channelled around the Southern Alps to the north, the resulting near surface wind direction observed along the east coast of the South Island is often from a north-east direction. The onshore north-easterly is induced under localized pressure gradients that form in the lee of the Southern Alps, affecting the passage of airflow between the North and South islands of New Zealand [29]. This trough-induced north-easterly [35] is most frequent in summer months and has been shown to interact with the thermally induced sea breeze to complicate the regional wind field along the east coast of the South Island [48]. These wind regimes have been comprehensively studied in the vicinity of Christchurch (Fig. 1) (e.g. Refs. [29,35,48]), but not in regions to the south.

Operating over the mesoscale, sea breezes result from the differential response to heating and cooling between land and sea surfaces. A land-sea temperature gradient of sufficient magnitude generates landward (during the day) thermal pressure gradients to drive onshore airflow, known as the day time sea breeze. In many locations, the typical depth and wind speeds associated with the sea breeze circulation imply that the sea breeze is potentially capable of providing momentum for power generation at times where otherwise weak synoptic gradients would inhibit this [13,32]. On the other hand, in certain locations the implications of the sea breeze might have detrimental consequences for coastal or offshore wind power generation, as demonstrated through idealized numerical model simulations in the studies of [45] and [19]. Sea breezes have been observed to occur in all coastal regions of New Zealand [50], however, examination of sea breeze dynamics has been limited to select regions (e.g. Refs. [25,48]). In such regions, the sea breeze can be complicated by other dynamical and thermal effects, creating a spatially complex wind field that is difficult to forecast [48].

Generally, the strength of the sea breeze is proportional to the land-sea temperature gradient, while ambient synoptic flow is also well known to affect several aspects of the sea breeze circulation. Several studies note that the influence of offshore ambient synoptic winds on various aspects of the sea breeze can critically depend on the strength of the larger scale circulation (e.g. Refs. [6,16,18,44,45]). In review of various numerical modelling studies, [12] suggest the various thresholds found concerning the influence of offshore synoptic flow on the sea breeze reflects the different land-sea temperature contrasts between studies. However, terrain complexity in coastal regions can also complicate the classical understanding of the linkage between ambient synoptic winds and the sea breeze circulation, as demonstrated in Ref. [48].

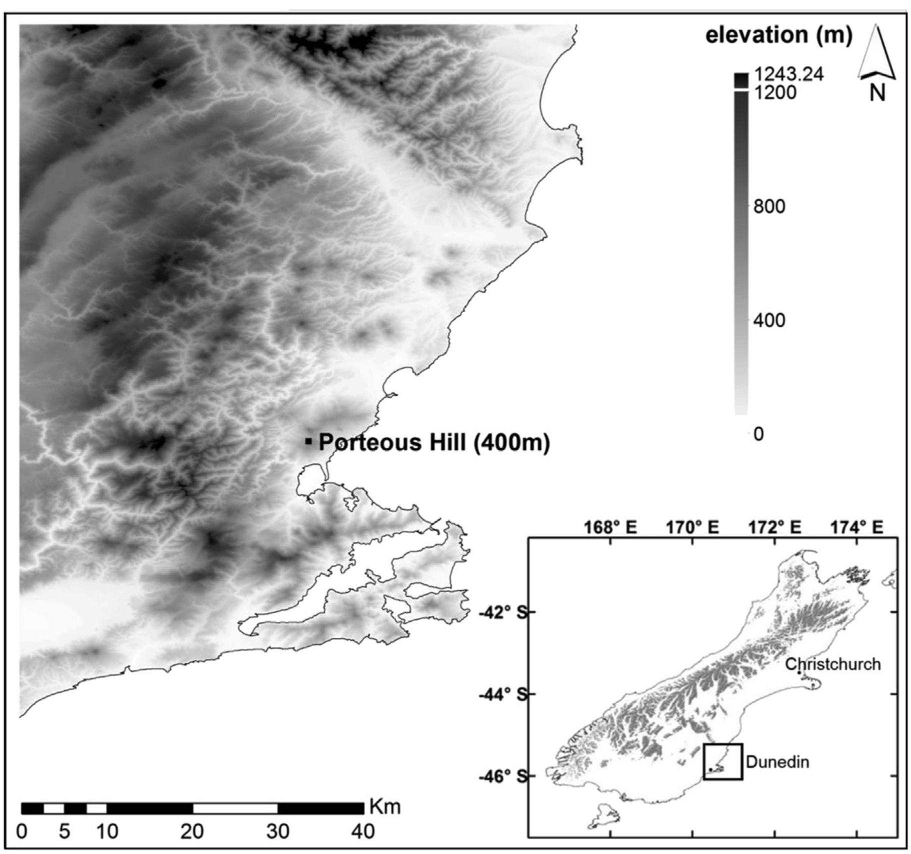

Fig. 1. (Lower) Position of Dunedin relative to the south-west to north-east aligned Southern Alps in the South Island of New Zealand; grey shading indicates elevation > 1000 m. (Upper) Enlarged map (area contained within square box in lower map) showing the elevation of terrain surrounding Dunedin.