Ministry for Primary Industries
Manatū Ahu Matua

DEVELOPMENT OF ADVANCED WEATHER AND CLIMATE MODELLING TOOLS TO HELP VINEYARD REGIONS ADAPT TO CLIMATE CHANGE

Part 1

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Executive summary

The aim of this research is to provide new knowledge and develop practical tools to help the New Zealand wine industry to adapt to climate changes and variability across a range of time and space scales. The research brings together the expertise of scientists specialised in regional and local climate analysis and modelling with specialists in grapevine physiology, and phenological and crop modelling.

The research methodology involved the collection of field data in the Marlborough vineyard region, including meteorological measurements obtained from an enhanced automatic weather station (AWS) network and observations of grapevine development in selected vineyards, as well as high-resolution meteorological modelling using the state-of-the-art Weather Research and Forecasting (WRF) model.

Simplistic application of IPCC scenarios to predict possible future climatic conditions in Marlborough suggested that climate model predicted increases in mean temperature over the next few decades (up to about 2030-2050) are likely to lie within the typical inter-annual variability currently observed in New Zealand's vineyard regions, while by the end of the century (2080-2100) they would lie outside this range and would therefore be of significant concern to the wine industry.

Detailed analysis of air temperature trends in vineyard regions over recent decades provided the context for the research, and showed that the problem of assessing impacts of climate change on the country's vineyard regions is more complex than suggested by simply applying IPCC scenarios based on global models. In particular, differences in temperature trends between vineyard regions were identified and found to be associated with changes in regional weather patterns resulting from major shifts in the location of the main atmospheric circulations features in the Southern Hemisphere, as reflected in recent trends in the Southern Annular Mode and the M1 index.

A key feature of recent temperature trends is the observed increase in daily temperature range in a number of areas in New Zealand, hence increasing the risk of frost during critical phases of grapevine development in some vineyard regions (particularly in Marlborough – the country's premier wine-producing region). It also appears that mean annual temperatures in New Zealand's vineyard regions have not continued to increase over the last ten years, and that this is in line with a global slow-down in the global warming trend since 1999.

The data collected over two growing seasons (2013-14 and 2014-15) have been used to validate the output of the high-resolution weather/climate model (WRF) and to evaluate the ability of the new Grapevine Flowering Véraison (GFV) phenological model to predict grapevine response in New Zealand climatic conditions. The validation tests indicate that the WRF model simulations of 2-m mean daily air temperature have a slight cold bias that is consistent throughout the growing season and across the region, but otherwise the model performed well. The GFV model performed well, but model parameters may need adjustment to the unique conditions of the cool climate vineyard regions of New Zealand.

WRF has therefore been used to provide 24-hour predictions of hourly near-surface temperature and wind fields at 1 km resolution over the Marlborough region that have been updated twice daily on the project web site throughout the growing season. These data are also used to provide detailed maps of accumulated growing degree-days (GDDs) based on the GFV model that have also been automatically updated daily on the web site throughout the season. The GFV model has been used to simulate the spatial variation in the flowering date of Sauvignon blanc across both the Marlborough and Waipara regions based on temperature data from both AWS and the WRF model. The results for the 2013-14 season indicate that there is good agreement between simulated and observed dates of flowering at test sites across the Marlborough region. Analysis of results for the 2014-15 growing season is still under way.

The WRF model has also been run retrospectively over the growing seasons since 2008-9, allowing detailed spatial and temporal analysis of the climate and grapevine response over several contrasting seasons. A variety of climate variables has been examined, including maximum, minimum and mean daily temperatures, growing degree-days, and flowering and véraison dates for the growing season, to give an indication of the regional variation in air temperature and its effect on grapevine response on an inter-annual basis. Results showed that the growing seasons since 2008-9 have experienced relatively small inter-seasonal variability compared to the 1990s (in line with temperature variability nationally), but that there is significant spatial variation of temperature due to effects of topography and distance from sea. This spatial variability suggests that there is some robustness of the region to longer-term changes of climate (for example, associated with global warming), as there is a wide range of sites within the Marlborough region where grapes could be grown under present and predicted near-future climate conditions. The maps also provide an insight into the characteristics of both very good growing seasons in the Marlborough region, such as 2013-14, as well as poorer seasons like 2011-12.

A ‘wine-climate’ web site has been constructed as part of this project to provide a tool for communicating the results of the research to the stakeholder community. In addition to maps and graphs obtained from the WRF and phenological modelling, general information about the research is also provided on this site, as well as discussion of strategies to help the wine industry adapt to climate change and variability. These are categorised under long term and short term responses that include the selection of appropriate grape varieties and rootstocks, as well as application of a range of canopy management techniques to slow down or speed up grapevine development during the growing season.

This ambitious project has developed a new approach to investigating the relationship between climate variability (particularly the thermal climate) and grapevine response. This approach is based on integration of measurements of both climate and grapevine response with advanced weather/climate modelling techniques. The results have demonstrated that this approach can generate significant new knowledge about climate variability within vineyard regions, and provides the basis for assessing the impact of longer term climate change at the global and regional scale, and for developing adaptation strategies to help vineyard regions in New Zealand and elsewhere respond to climate change.

Having demonstrated the effectiveness of our integrated research strategy to improving knowledge of climate variability in two of New Zealand’s major vineyard regions, further research is planned to further test, refine and apply this approach in other parts of the country and the rest of the world, through collaboration with the international research community via our strong links with European researchers. The innovative methodology developed in this research project can also be applied to a range of other crops, and opportunities will be sought to extend the research into other agricultural areas.

1. Introduction

New Zealand wine export volumes have doubled between 2005 and 2011, reaching $1,104 million (Ministry of Agriculture and Forestry 2011). They were at around $1,330 million in 2014 (New Zealand Winegrowers annual report 2014 - http://www.nzwine.com/assets/sm/upload/b5/2j/rr/2n/NZW%20AR%202014_web.pdf), but the wine industry remains vulnerable to climate variability, as it affects both wine quantity and quality, as shown worldwide (Jones and Davis 2000, Jones et al. 2005, van Leeuwen et al. 2004). Grapevines are highly sensitive to environmental conditions, with each variety having an optimal temperature range within which it will produce a definitive wine style (Jackson and Lombard 1993). New tools will allow better decision-making that will both improve returns on investment and reduce costs. This refers to both short-term operational decisions such as pruning regimes, canopy management, and response to frost and disease occurrence (Webb et al. 2012), and longer-term decisions related to planting of grape varieties to ensure that they are ideally suited to environmental conditions. It is evident from some initial research into trends in frost occurrence (Clark and Sturman 2009) that there are significant differences in observed climate variability between the main vineyard regions of New Zealand shown in Figure 1, so that one cannot assume that temperature changes are the same throughout the country (e.g. frosts are increasing in Marlborough, but not in other areas). These regional differences appear to be caused by changes in the large-scale atmospheric circulation and its interaction with the complex terrain of New Zealand (Sturman and Quénol 2013). Latitude is a key factor causing climate differences between the vineyard regions as they stretch from < 37°S to > 45°S, while the complex terrain of New Zealand strongly affects regional patterns of temperature and rainfall. The strong sensitivity of the wine industry to variations in weather and climate and the significant regional variability in trends of key parameters such as temperature means that increased knowledge of spatial and temporal variability of weather and climate in New Zealand is of significant value to viticulture.

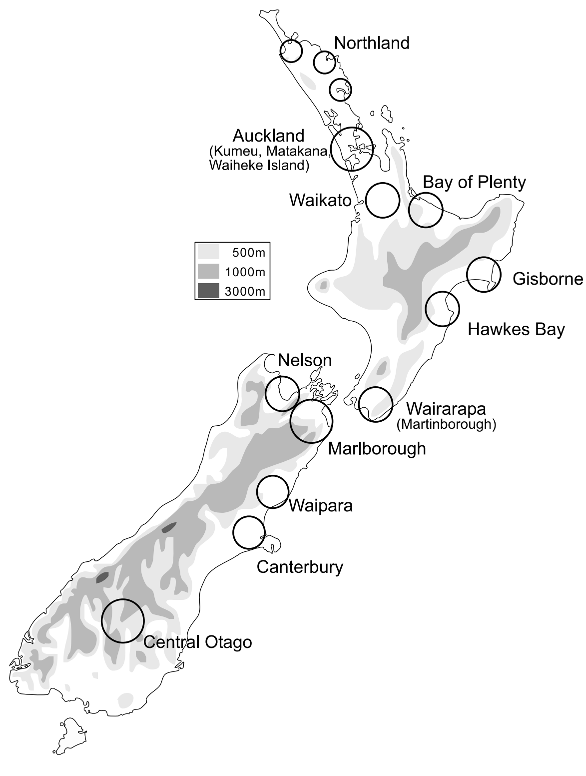


Figure 1: The main vineyard regions of New Zealand (Sturman and Quénol 2013). Circles indicate the general location of vineyard regions only, while the sites used in this report to represent the main wine-producing regions are Queenstown (Central Otago), Christchurch (Canterbury), Blenheim (Marlborough), Nelson (Nelson), Napier (Hawkes Bay).

1.1 BACKGROUND/AIMS

The main aim of this research is to generate new knowledge and decision-making tools to help the wine industry respond to variations of climate at different scales, from selection of suitable grape varieties to application of appropriate vineyard management techniques. This new knowledge will result from both analysis of existing meteorological data at a range of scales from hemispheric to local, and application of advanced local and regional scale weather and climate models and their integration with new grapevine phenological and crop models. While the thermal environment of the grapevine will be the main focus of this research, as air temperature continues to be the basic parameter used in the development of such models, other environmental and management factors that affect vine phenology are not ignored. For example, soil type (in particular soil water holding capacity and/or texture) may influence phenology at a particular site (Tesic et al. 2001, Trought and Bramley 2011), but it seems likely that warming temperatures will advance vine development to a similar degree and the relative differences between soil types will remain comparable. Likewise, grapevines have a winter chilling requirement for rapid, even bud burst in the spring (Londo and Johnson 2014). However, relatively cold Marlborough winters, make it likely that inadequate chilling will be of greater importance in warmer climates before it becomes a problem in Marlborough.

Marlborough provides the initial focus of this research because about 75% of New Zealand's vineyards are located in this region and Sauvignon blanc, predominantly grown in Marlborough, represents 85% of the export volume. The complex terrain surrounding the vineyard region shown in Figure 2 creates significant spatial variation of climate (Sturman et al. 2014, Powell 2014). At the larger scale, the weather and climate characteristics of the region result from the interaction of the mountainous region to the west with the eastward movement of anticyclones and intervening troughs of low pressure. Anticyclones passing close to the region result in light prevailing winds, so that thermally induced local wind systems often become established. These include slope and mountain and valley winds, as well as sea and land breeze circulations, particularly near the coast. These circulations typically result in a daily reversal in wind direction, with the daytime coastal sea breeze acting to cool the eastern coastal part of the region, while western areas are often affected by nighttime cold air drainage. The sheltering effect of the terrain can also result in light winds or stagnant conditions that can influence temperature patterns, including the occurrence of frost (Powell 2014).

Active troughs and low-pressure systems that pass over the region are the main source of significant rain, either in the form of orographic spillover from the western ranges or coastal showers in easterly flows. The region is significantly affected by the rain-shadow effect of the Southern Alps and its foothills so that it is one of the driest regions in the country. As a result, a high number of sunshine hours are recorded in the eastern part of the region, with an annual average of almost 2500 hours (http://cliflo.niwa.co.nz). Table 1 provides a summary of the key climate variables for the Marlborough Research Centre site near Blenheim (meterological data can be downloaded from http://www.mrc.org.nz/category/weather-data/blenheim-weather-data/). According to a recent global assessment, the whole of New Zealand falls into the Cfb (warm temperate, fully humid, warm summer) and Cfc (warm temperate, fully humid, cool summer) categories of the Köppen-Geiger climate classification system (Kottek et al. 2006). However, several national scale climate classifications have shown that significant regional climate variability is evident across New Zealand, as described by Sturman and Tapper (2006).

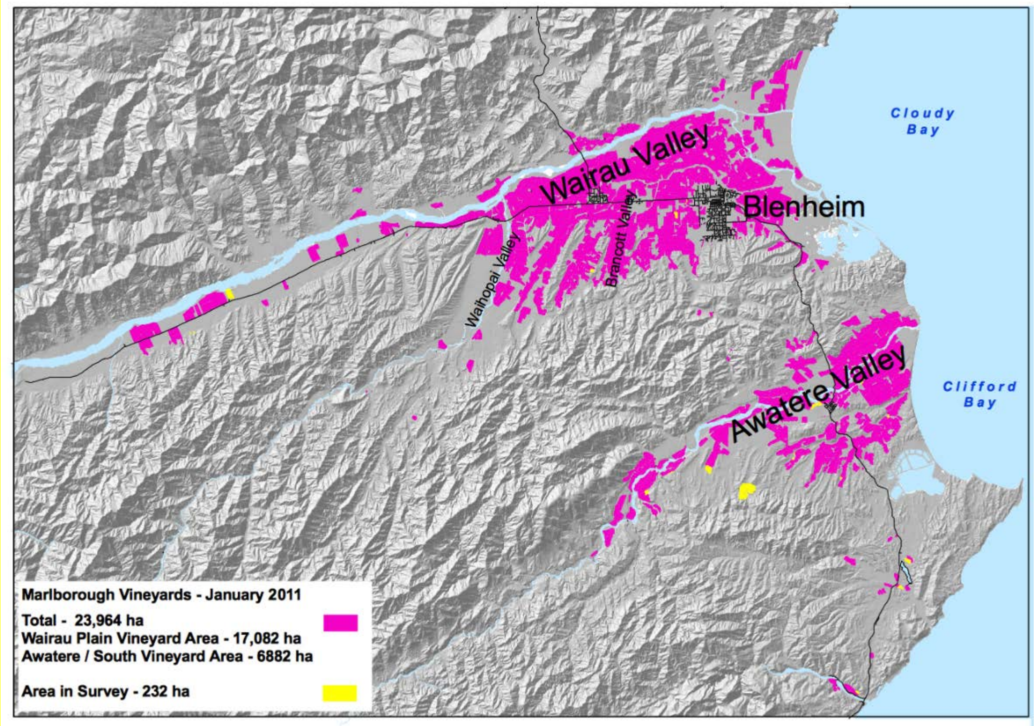


Figure 2: Map of the areas covered by vineyards in the Marlborough region and the location of the Wairau and Awatere Valleys and the urban area of Blenheim (modified after a map provided by the Marlborough Regional Council).

In summary, the climate of the Marlborough vineyard region (Table 1) is affected by the coastal influence that is reduced with distance inland, as well as terrain-induced local wind systems that have a feedback effect on the thermal regime, particularly under anticyclonic weather conditions. Table 1 provides climate data for only one site, but in fact there is marked spatial variation in temperature and rainfall patterns across the region. For example, average annual rainfall increases from 600 to 1200 mm from south to north across the Wairau valley, a distance of only 8 km (Figure 3). Heavy rain and strong winds do not generally have a significant impact in the Marlborough region, so that frost and possibly extreme high temperatures represent the most significant climate risks for viticulture under the present climate regime. The new knowledge and analytical tools developed by this research have had to take account of the significant challenges provided by the complex small-scale variability in the atmospheric processes of the region.

Table 1: Summary of Blenheim (NZ MetService site G13592) meteorological conditions (N.Z. Meteorological Service 1980).

	J	A	S	O	N	D	J	F	M	A	M	J	Yr
Rain[1] (mm)	62	65	49	55	46	46	50	44	45	56	68	56	642
Rain days[1] (=< 1mm)	8	8	7	8	7	7	5	5	6	6	7	7	81
Mean daily[2] T (°C)	7.0	8.3	10.5	12.6	14.6	16.7	17.8	17.8	16.2	13.4	10.1	7.4	12.4
Avg daily[2] max (°C)	16.7	18.0	21.1	24.3	26.5	29.0	31.0	30.0	28.1	24.9	20.8	17.9	31.9
Avg daily[2] min (°C)	1.5	3.0	5.1	7.2	8.9	11.0	12.0	12.1	10.5	7.9	4.7	1.9	7.2
Sunshine[3] (hr)	158	175	195	227	239	245	260	228	214	188	165	153	2447

[1]1930 – 1980, [2]1932 – 1980, [3]1935 – 1980

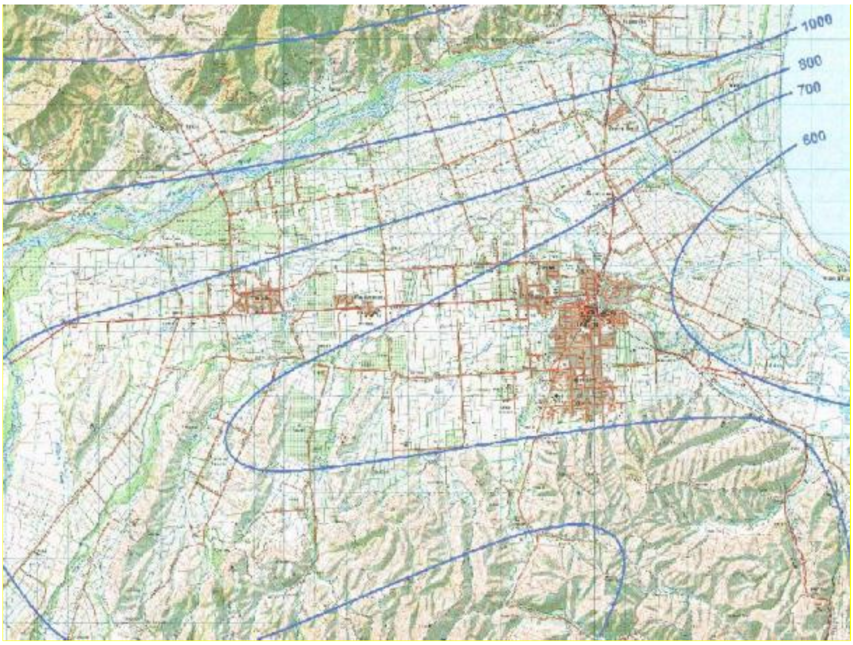


Figure 3: Marlborough annual rainfall isohyets for the Wairau Plain (adapted from Map 3.1 in Rae 1988).

It should also be mentioned that there has been significant land-use change in this region since the 1970s as a result of vineyard development (see Figure 4), which is likely to have had some impact on the local climate, particularly due to the widespread use of irrigation and removal of shelterbelts. The tools developed in this project could also be used to assess the significance of this effect.

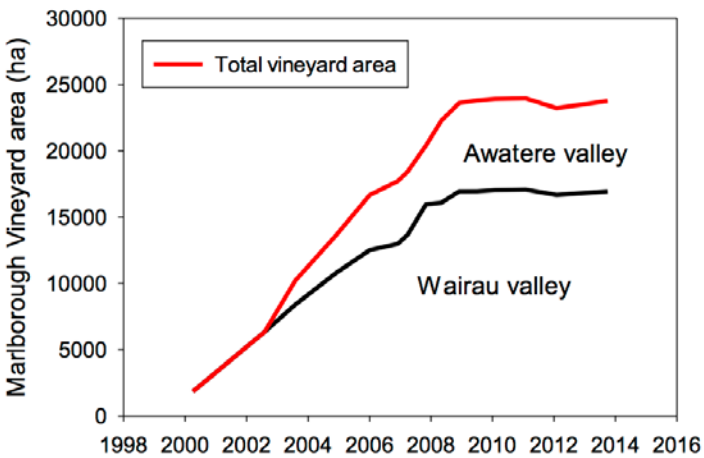


Figure 4: Increase in area planted in vineyards in Marlborough 2000 to 2013 (http://www.marlborough.govt.nz/Environment/Land/Land-Cover-Land-Use/Crop-Types.aspx).

While the region can be geographically divided into two valleys (the Wairau to the north and Awatere to the south), most of the vineyard area is encompassed within a circle of diameter 45 km (Figure 2). The two valleys, separated by a range of low hills (the Wither Hills) up to 750 m high, provide for some distinct differences in climate. In general, both valleys are subject to northwest winds, particularly in the spring, although the Awatere Valley has greater exposure to cool southerly winds and spring frosts, it also experiences lower rainfall. In general, while the vineyards in the Awatere Valley have a lower yield potential, adverse events affect vineyards in both valleys in a similar way (i.e. a frost or drought conditions in one valley will generally be reflected in the other).

Seasonal differences in weather conditions can have a significant effect on grapevine yield in the Marlborough region (Table 2). Drought, spring frost damage, rainfall during the harvest period (which can result in increased botrytis bunch rot) and temperature during the December/January period (which largely determines bunch number in the following season and bunch weight in the current season (Trought 2005, Vasconcelos et al. 2009)) are important in determining the fruit quality and stability of supply. Regional rainfall generally occurs as short duration, relatively high intensity events and as a result most vineyards have trickle irrigation to supplement rainfall. Similarly, vineyards in what are considered to be frost sensitive areas either have protection systems (there are approximately 1,200 frost fans in the Marlborough region or overhead water sprinkler protection) or use helicopters to protect vines from spring or autumn frost. Vineyards with no protection are at considerable risk in some seasons (see Appendix D). The improvements in recent years of the 10 day weather forecasts has enabled wineries to anticipate wet weather over the harvest period and manage fruit harvesting schedules accordingly. Despite that, rain in late harvest (particularly in 2014 when two intense events between 8 and 10 April [57 mm] and 13 and 15 April [70 mm] resulted in botrytis epidemics) can abruptly terminate harvest. The seasonal fluctuations in grapevine yield have caused problems in the supply chain (inadequate tank space in the winery and an imbalance in the market supply:demand ratio, affecting grape and wine prices), while also affecting the opinions of wine journalists of the quality of the vintage (they generally associate high yields with inferior quality). Of particular note were the 2009 and 2014 seasons where high yields, caused by above average initiation and flowering temperatures, resulted in an oversupply of fruit.

Table 2: Seasonal Sauvignon blanc yields and key meteorological parameters.

Season	National Sauvignon blanc yield (T)[1]	Predicted Marlborough Sauvignon blanc yield[2] (% long-term average)	Seasonal GDD (base 10^{o}C) (1 Sept to 30 April)[3]	Seasonal rainfall (mm) Sept. to April[3]	Harvest rainfall (mm) March and April[3]
2007-8	169,613	92	1372	408	164
2008-9	177,647	133	1254	454	66
2009-10	174,247	136	1310	305	40
2010-11	224,412	157	1336	425	98
2011-12	181,121	99	1343	431	93
2012-13	228,781	134	1318	319	124
2013-14	310,240	160	1363	462	176

[1]Data are unavailable for Marlborough Sauvignon blanc yields alone, although it represents approximately 80% of the national yield.
[2]The Marlborough regional Sauvignon blanc yield has been estimated using a yield prediction model (Trought 2005). This uses temperatures at bunch initiation and flowering to provide an estimate.
[3] downloaded from http://www.mrc.org.nz/category/weather-data/blenheim-weather-data/

1.2 INTERNATIONAL CONTEXT

International research has identified climate variability within vineyard regions of the world and the likely need to move vineyards to cooler coastal areas, such as in Australia (Webb et al. 2007, Hall and Jones 2010), New Zealand (Salinger 1987), South Africa (Bonnardot and Carey 2008) and North America (Lobell 2006, White et al. 2009, Jones et al. 2010). Since the early

2000s, the availability of global climate model output has enabled the initiation of research into modelling the effects of future climate on the viticultural world. The calculation of bioclimatic indexes based on different scenarios of the IPCC has indicated significant likely changes in the distribution of vineyards through to 2070-2100, with the disappearance of vineyards in areas such as southern Australia and the Mediterranean countries, and the development of new areas such as northern Europe (Hannah et al. 2013). However, such studies have tended to be restricted to the larger (regional) scale and their usefulness for developing local adaptation strategies is therefore limited. There has been little research into the future impacts of climate change on agro-climatic potential at the fine ("terroir") scale. It is already apparent that in some wine regions variability in atmospheric parameters over relatively small areas (of the order of a few kilometres to a few metres) is very important (Quénol 2014), and the quality of grapes and/or wine is often related to the influence of local characteristics such as slope, aspect, soil, etc. In recent years, several international programmes have started to make measurements (weather and agronomic) and undertake meteorological modelling at fine scales with the aim of defining the climate of the local "terroir" and the identifying impact of climate change at vineyard scale. This work has been initiated in several vineyard regions across the world in which climatic characteristics are known to have an important effect on wine quality (Quénol 2014). Some studies have investigated the local agro-climatic potential of soils in different macroclimatic conditions – for example, Smart (2014) studied the climate potential at small scales in Tasmania by installing a network of temperature loggers. In France, several programmes have recently investigated local variability of the vineyard climate in the context of climate change, and initial results suggest that local variability of the climate within vineyard regions can be of the same order of magnitude as variability between regions (Ollat and Touzard 2014, de Resseguier et al. 2014, Quénol and Bonnardot 2014). The present study therefore involves collaboration with key international programmes and scientists with the aim of investigating the sustainability of the New Zealand wine industry in the context of global climate change.

1.3 METHODOLOGY

Methods are urgently needed to quantify seasonal fluctuations in grapevine phenology and yield in order to adapt to changing yields or fluctuations in wine style. Managing yields year-to-year is important because consistency of wine style is considered to be a key characteristic of New Zealand wine. There is a preference to try to maintain a consistent wine style so that the market knows what to expect when buying wine from New Zealand producers. Also, geographic factors produce significant regional and local climate variability to which many vineyard areas have become adapted. This spatial variability of climate affects the robustness of a vineyard region to long-term climate change, because as some parts of the region may become unsuitable for specific grape varieties, other parts may take their place (Jones et al. 2009, Seguin and Garcia de Cortazar-Atauri 2005). Investigation of small-scale climate variations within existing vineyard areas is therefore an important first step in developing a strategy for adapting to climate change. Improved knowledge of possible regional and local variations in climate also depends on a better understanding of the relationship between large-scale atmospheric circulation and processes that operate at a smaller scale (Bonnardot et al. 2002, 2005, 2012). The current research therefore adopts a multi-scale approach that has been developed to address this problem by integrating measurement and modelling techniques at a range of time and space scales.

The first phase of the research involved a detailed assessment of the present-day climate resource available to support viticulture in selected areas, including the application of improved technology to both collect new data and to model climate, and subsequently plant response, at high spatial and temporal resolutions. The methodology used in this research, illustrated in Figure 5, involved a number of different objectives:

Objective 1

- Investigation of recent temperature trends in New Zealand vineyard regions through analysis of existing climate data.
- Identification of the effects of changes in larger scale atmospheric circulation on observed temperature trends in New Zealand vineyard regions in order to provide a causal link between global, hemispheric and regional climates.

Objective 2

- Measurement of climate at the regional scale (km) using an enhanced network of sensors and data loggers located to capture the range of topographic situations within a selected vineyard region (e.g. slope, aspect, altitude and location in the terrain) and different soil types.
- Application of high-resolution weather and climate and phenological modelling to map the climate and potential plant response at regional (1-3 km) and vineyard (100s m) scales, validated using the measurements mentioned above. Other researchers have applied weather and climate models to improve understanding of the regional and local climate variability in vineyard regions (Bonnardot and Cautenet 2009, Bonnefoy et al. 2010), but no-one has so far attempted to couple such atmospheric models with phenological models to assess effects of climate variability on the grapevine.

Objective 3

- Relate fine-scale spatial patterns of climate to grapevine response and wine production using bioclimatic indices and phenological and crop models to assess the optimal or marginal status of different grape varieties, and the extent of environmental risk (e.g. frost or extreme high temperatures).
- Apply new integrated climate-phenological models to simulate temporal and spatial variability of phenological stages and develop fine-tuned adaptation strategies based on vine and/or soil moisture manipulation (see Parker et al. 2011, Parker et al. 2013, Webb et al. 2012).

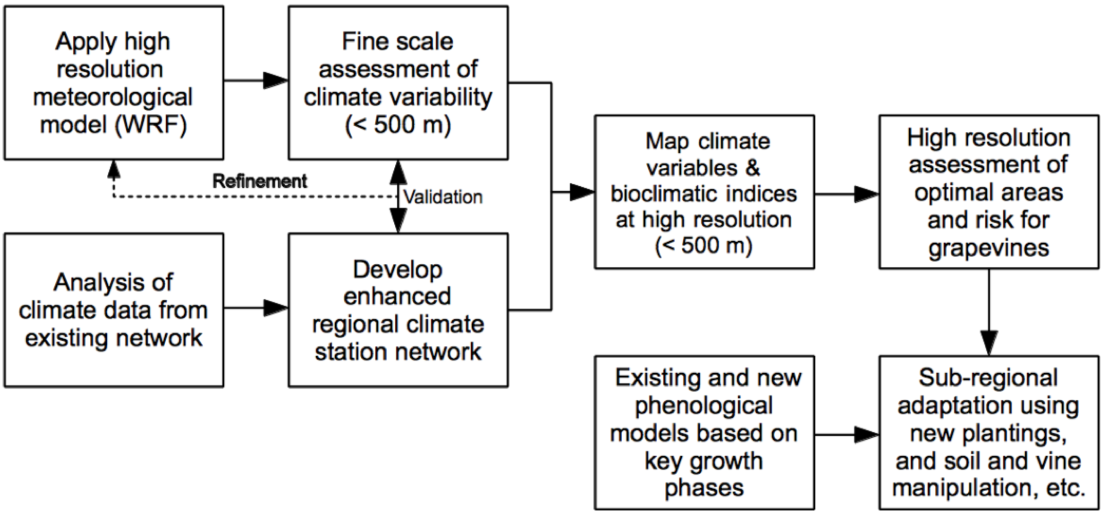


Figure 5: Schematic illustration of the methodology of the proposed research.

This research includes data collection, three-dimensional atmospheric numerical modelling, statistical techniques, phenological and crop modelling, and geographic information systems. These techniques are applied initially to the Marlborough study area, and subsequently to the Waipara vineyard region, with the aim of applying them to other regions in the future. Understanding impacts of changing climate on viticulture requires good knowledge of local climate processes within vineyard areas, so that measurement and modelling of climate at high resolution (kms to 100s of metres) is an important component. Recent development of advanced computer modelling capability allows high-resolution atmospheric modelling to complement and extend measurement networks, improving understanding of the processes responsible for local scale climate variability. Geo-statistical modelling allows evaluation of adaptation strategies for maintaining the long-term sustainability of vineyard areas in a changing climate, as well as exacerbation of risk factors (e.g. frost, heatwave, and cool spells) due to predicted future climates.

1.3.1 The enhanced network of weather/climate stations and temperature loggers in the Marlborough vineyard region

Following a detailed assessment of available data for the area, and in consultation with landowners, an enhanced network of weather stations in Marlborough was designed and installed (Figures 6 and 7). In mid-2013, eleven new automatic weather stations were added to the existing network owned and operated by Plant and Food Research Ltd, Stu Powell and MetService, with the aim of extending coverage to data sparse areas. This helps to better describe the meso-climate of the Marlborough region and provides additional observed data to validate the numerical model outputs. In parallel, an additional 39 sites were selected in the Brancott Valley at which air and soil temperature loggers were installed. This provided an intensive array of temperature sensors at a much higher resolution to assess the ability of advanced downscaling techniques to reproduce fine-scale variations in temperature in an area of complex terrain.

The eleven additional automatic weather stations recorded meteorological data every 10 minutes, while time-lapse cameras took pictures of the vineyard every 3 hours between 7 am and 7 pm in order to monitor phenological grapevine stages (and meteorological events such as frost and fog). The heights of the different sensors above ground level were as follows:

- Wind speed and direction at 5 m
- Air temperature at 5 m
- Solar radiation at 3.4 m
- Time-lapse camera (facing north, taking pictures of vineyard) mounted at 3 m
- Air temperature and relative humidity at 1.5 m
- Pressure (sensor mounted inside the logger box) at approximately 1.3 m
- Soil moisture at -2 cm
- Soil temperature at -2 cm
- Soil temperature at -30 cm

The main variables of interest to viticulture were collected, including air temperature at two heights (to allow assessment of temperature inversion strength), wind speed and direction, relative humidity (for its relevance to fungal diseases of the grapevine), solar radiation and air pressure. A time lapse camera was set up to record changes in the vine canopy during the growing season. Soil parameters were also monitored, including soil temperature and moisture, because they are standard parameters of significance to atmospheric modelling. The vineyards themselves are all trickle irrigated so that spatial and temporal variability in soil moisture in vineyards is very small. This is in contrast to other parts of the world where irrigation is either forbidden or not part of the vineyard management regime.

It was decided to continue data collection through two full growing seasons, starting in May 2013 through to May 2015, to provide sufficient data to adequately validate the meteorological and phenological models. An inter-site calibration programme involving the use of a mobile high-specification weather station ensured that the spatial variation of weather within the vineyard area was recorded accurately, and that the data are appropriate for model validation.

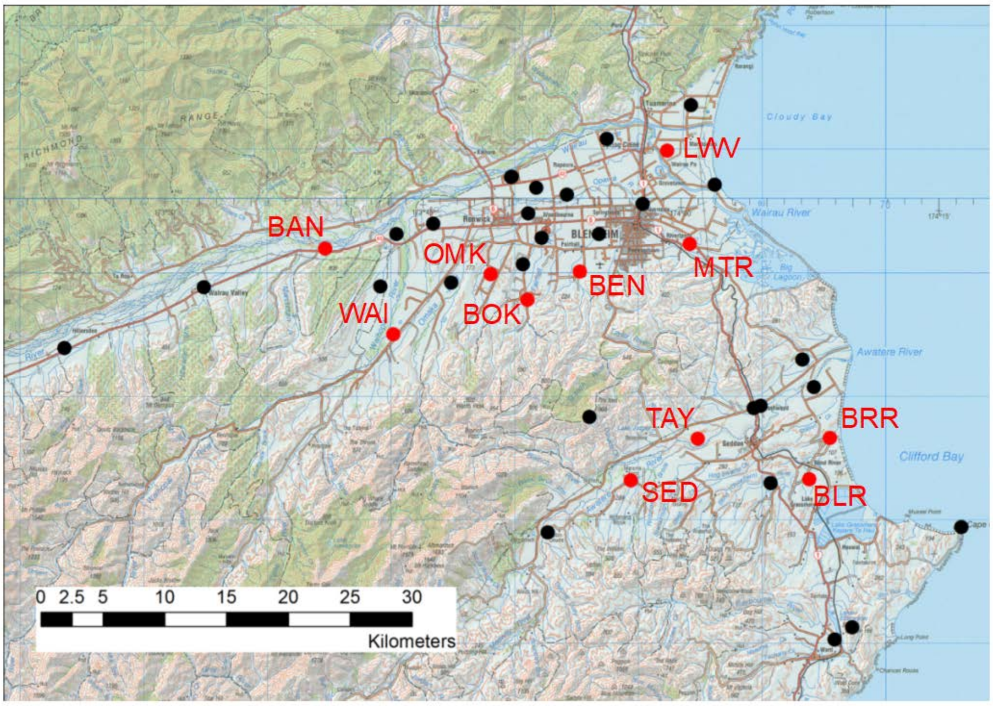


Figure 6: Map of the enhanced network of automatic weather stations in the Marlborough vineyard region. The red dots indicate additional stations installed specifically for this study, with site names: BAN = Bandalero, WAI = Waihopai Valley, OMK = Omaka Valley, BOK = Booker, BEN = Ben Morven, LWV = Lower Wairau Valley, MTR = Mt. Riley, TAY = Taylor's Pass, SED = Seddon Vineyard, BLR = Blind River and BRR = Blind River Reserve.

Figure 7: The automatic weather station at the Booker site.

1.3.2 The high resolution weather/climate modelling system

To complement the meteorological measurements, the advanced physics-based three-dimensional numerical weather model (Weather Research and Forecasting – WRF; http://wrf-model.org/index.php) has been used to represent high-resolution spatial variation of the meteorology over complex terrain within the Marlborough vineyard region over a time frame from hours to years, with model output validated using data from the enhanced weather station network. The WRF model runs use a set of nested grids to allow the downscaling of larger scale atmospheric processes to the local scale, where the influence of complex terrain can be represented by the high-resolution grid (Figure 8). The nested grid approach is based on grid dimensions shown by the black boxes in Figure 8a. This approach allows enhanced model spatial resolution (27, 9, 3 and 1 km, respectively), while preserving practical computer run times. The model configuration was selected based on numerous experiments and optimizations aimed at properly resolving the variation of climate within the region, and the key physics schemes used in the WRF model runs are listed in Table 3.

Hourly meteorological data are currently obtained operationally at 1 km resolution over the Marlborough region from the WRF model to allow reasonably high resolution mapping of variables that are important to viticulture (as shown in Figure 8b). Bioclimatic indices that reflect the response of the grapevine to its environment, such as the Grapevine Flowering Véraison model (GFV) (Parker et al. 2011), are also being derived from mean daily air temperature data obtained from model output. In addition to modelling the weather/climate at high spatial (1 km) and temporal (hourly) resolution during the two-year intensive analysis period (May 2013 to May 2015), the model has been run retrospectively for the five growing seasons since 2008-9 to allow comprehensive validation of model performance and comparison between contrasting seasons.

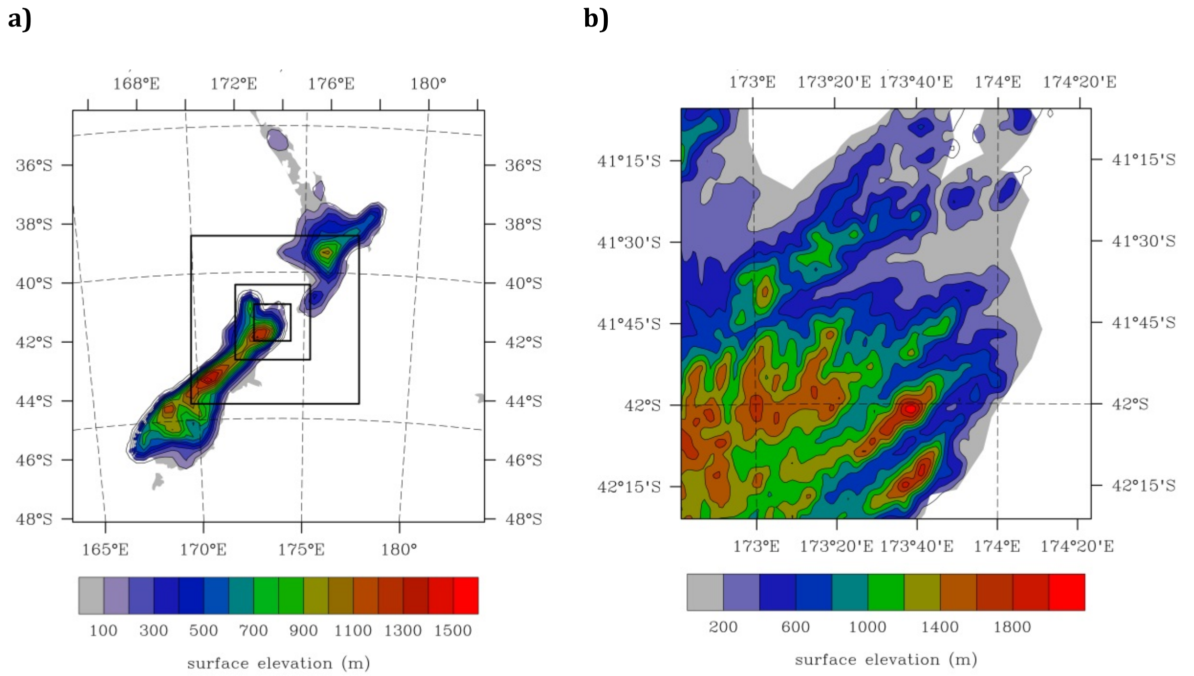


Figure 8: Weather Research and Forecasting model nested grid configuration, showing terrain height, a) for all four grid domains, and b) the high-resolution domain (grid 4).

Table 3: Physics schemes used in the Weather Research and Forecasting model runs.

	Scheme used	Source
Microphysics	Kessler	Kessler (1969)
Long-wave radiation	RRTM	Mlawer et al. (1997)
Short-wave radiation	Dudhia	Dudhia (1989)
Surface layer	Monin-Obukhov	Janjic (1994)
Land surface scheme	NOAH LSM with four soil layers	Ek et al. (2003)
Boundary layer scheme	Yonsei University (YSU)	Hong et al. (2006)
Cumulus parameterisation	Updated Kain-Fritsch scheme (domains 1 and 2 only)	Kain (2004)

1.3.3 The Grapevine Flowering and Véraison model

The output of the mesoscale atmospheric model is being incorporated into grapevine phenological models in order to assist in the development of wine industry strategies to adapt vineyards to the consequences of climate change. These models aim to account for temporal and spatial variation in the timing of phenological events often using temperature as a key determinant of phenology (Reaumur, in Chuine et al. 2013). The Grapevine Flowering Véraison (GFV) model (Parker et al. 2011) was calibrated for *Vitis vinifera* L. on a temporally and spatially diverse dataset, and then parameterised for approximately 100 different varieties for both 50% flowering and véraison (the véraison date was identified as when 50% of the berries softened or changed from green to translucent for white varieties or changed colour for red varieties) (Parker et al. 2013). The model starts summing daily mean temperatures from the 60th day of the year in the Northern Hemisphere (equivalent to the 29 August in the Southern Hemisphere) with a base temperature of 0°C. The thermal summation value (F^*) for Sauvignon blanc is reported as F^* = 1282°C.d (Parker et al. 2013), while F^* values for other prevalent New Zealand varieties are listed in Table 4. Véraison assessment of Sauvignon blanc in Marlborough corresponded to assessing the softness of individual berries in a 32-berry sample by gently pressing on each berry. The proportion of berries that were soft was then calculated for each sample and recorded each day, and 50% véraison determined from the daily time series.

Table 4: Classification of some grapevine varieties using the Grapevine Véraison Model (see Parker et al. (2013) for critical degree-day sum values (F^*) of additional varieties).

Variety	F^* [1] flowering	F^* véraison	F^* véraison – F* flowering	Estimated difference in timing (days) of flowering relative to Sauvignon blanc (assuming a mean daily temperature of 16.5 °C)[2]	Estimated difference in timing (days) of véraison relative to Sauvignon blanc (assuming a mean daily temperature of 17.5 °C)[2]	Days flowering to véraison, assuming mean daily temperature of 17.5 °C
Sauvignon blanc	1282	2528	1246	0	0	71.1
Chardonnay	1217	2547	1330	-4.0	-1.1	76.0
Pinot noir	1219	2511	1292	-3.8	-1.0	74.4
Riesling	1249	2590	1341	-2.0	3.5	76.6
Merlot	1269	2636	1367	-0.8	6.2	78.1
Syrah	1279	2601	1322	-0.2	4.7	75.5
Cabernet Sauvignon	1299	2689	1390	1.0	9.2	79.4
Mourvèdre	1354	2706	1352	4.4	10.2	77.3

[1] F* is the critical degree-day sum (above 0°C, starting on the Northern Hemisphere 60th day of the year).
[2] Negative values indicate flowering or véraison is in advance of Sauvignon blanc, positive values indicate the phenological stage for that variety occurs after Sauvignon blanc. Mean daily temperature choices reflect the approximate mean temperature in December (16.5°C) and Feburary in Marlborough (17.5°C).

It has already been observed from initial tests for 50% flowering of Sauvignon blanc in the Marlborough region that there were some differences between predictions (GFV with F^* = 1282°C.d) and observations for some years and sites, with an average difference of 4.9 days (Parker et al. 2014a). Furthermore, the spatial and temporal variability used to calibrate the GFV model is the most diverse reported in the literature for grapevine phenological model development. Both these factors indicate that the GFV model is currently the most appropriate model for phenological models that start from a fixed date (in this case 29 August) to evaluate for the prediction of Sauvignon blanc flowering in the Marlborough region. Traditionally, temperature data used to generate flowering predictions in this type of phenological model are derived from nearby meteorological stations (Automated Weather Stations, AWS). However, it is also possible to use temperature data from the high-resolution Weather Research and Forecasting (WRF) model in combination with phenological models like the GFV model to generate predictions of flowering at high spatial resolution in vineyard regions. A key aim of this part of the work is to compare Sauvignon blanc flowering predictions using temperatures derived from both automatic weather stations and the WRF model with observations made in the vineyards, and to evaluate the validity of this approach.

The GFV model is considered to be the most appropriate model to test for flowering and véraison due to the fact it was calibrated on international historical data sets with a reasonable amount of spatial and temporal variation (Parker et al. 2014a). However, it should be noted that in New Zealand we do not have such long-term data sets, so that adjustment of model parameters will be needed as the amount of local input data increases. Further development of the model by members of the research group should help to improve the application of phenological modelling to viticulture, especially if the model is linked more closely to the development cycle of the grapevine rather than absolute time.

2. Analysis of variations of climate in the Marlborough region in the context of recent climate variability

To set the current research in a wider context, an initial assessment of medium and longer term climate predictions for the Marlborough region was undertaken based on IPCC scenarios. In order to evaluate the possible future temperature trends for the New Zealand region, the output of 12 global climate models has been analysed. These models, used to develop the global projections presented in the 4th report of the Intergovernmental Panel on Climate Change (IPCC 2007), were the subject of validation over the period 1970-1999 for the New Zealand and the South Pacific region (Mullan and Dean 2009).

The simulations were conducted using the scenarios A1B, A2 and B1 of the Special Report on Emissions Scenarios – SRES scenarios (IPCC, 2000) for the medium term (2030-2049) and the end of the century (2080-2099). Comparisons are relative to the 1980-1999 reference period, as used in the 4th report of the IPCC (2007). However, the horizontal spatial resolution of general circulation models (of the order of 200-300 km) is too coarse to account for the complexity of the changes at the local level, which is a recurring problem in the context of climate impact studies (Kim et al. 1984, Lamb 1987, Cohen 1990). Notwithstanding this limitation, the output of the 12 global climate models for both future periods (2030-2049 and 2080-2099) and the three scenarios of emissions (A1B, A2, and B1) have been integrated using regression models to allow downscaling of monthly temperature projections at the horizontal spatial resolution of 0.05° for the Marlborough region (see Philippe et al. 2013 for details). This approach is limited by the assumption that the relationship between regional and global scale trends in temperature are likely to remain the same. However, recent results described by Clark and Sturman (2009) indicate that the situation is more complex, in that observed trends in frost over New Zealand show significant regional variability with increased frequency of frost in some eastern areas (Figure 9). These results appear to disagree with the conclusion that a significant decrease in the number of frost days should be expected across the country since 1970 given the general increasing trend in temperature (Wratt, 2009). Also, Sturman and Quénol (2013) have demonstrated that there have been significant differences in temperature trends in New Zealand vineyard regions that appear to be related to the effect of changes in larger scale atmospheric circulation and its interaction with the complex terrain. Because of the complexity of the terrain in New Zealand and the sparse distribution of automatic weather stations across the country, the pattern of increased frequency of frost cannot be precisely known, although there is sufficient data available from existing stations to indicate that such increases have occurred in the areas indicated in Figure 9.

2.1 PREDICTIONS OF FUTURE CHANGE IN AIR TEMPERATURE BASED ON IPCC SCENARIOS

An increase of New Zealand temperatures of 0.9°C has already been recorded over the past 100 years (Mullan et al. 2008). Following this trend, the increase in annual average temperature in comparison with the period 1980-1999 should be between 0.7 and 0.9°C over the medium term (by 2030-2049), and between 1.3 and 2.5°C by the end of the century (2080-2099), respectively, for IPCC SRES scenarios B1 and A2 (Reisinger et al. 2010). Temperature projections across the Marlborough region for these future periods are very similar to that indicated for the whole country. Indeed, by considering only the grid points covering the region, the increase in annual average temperature should be between 0.7 and 0.9°C in the medium term, and between 1.3 and 2.6°C at the end of the century, respectively, for IPCC SRES scenarios B1 and A2 (Figure 10).

The analysis of monthly average temperature changes across the region reveals significant disparities in the magnitudes of warming. The months of October and November are expected to experience a less pronounced temperature rise under the different scenarios, between about

0.7 and 1.7°C, respectively, for the medium term and the end of the century. Comparatively, the months of February, July and August should register the largest increase, of the order of 1°C in the medium term and 2.2°C long term (Figure 11).

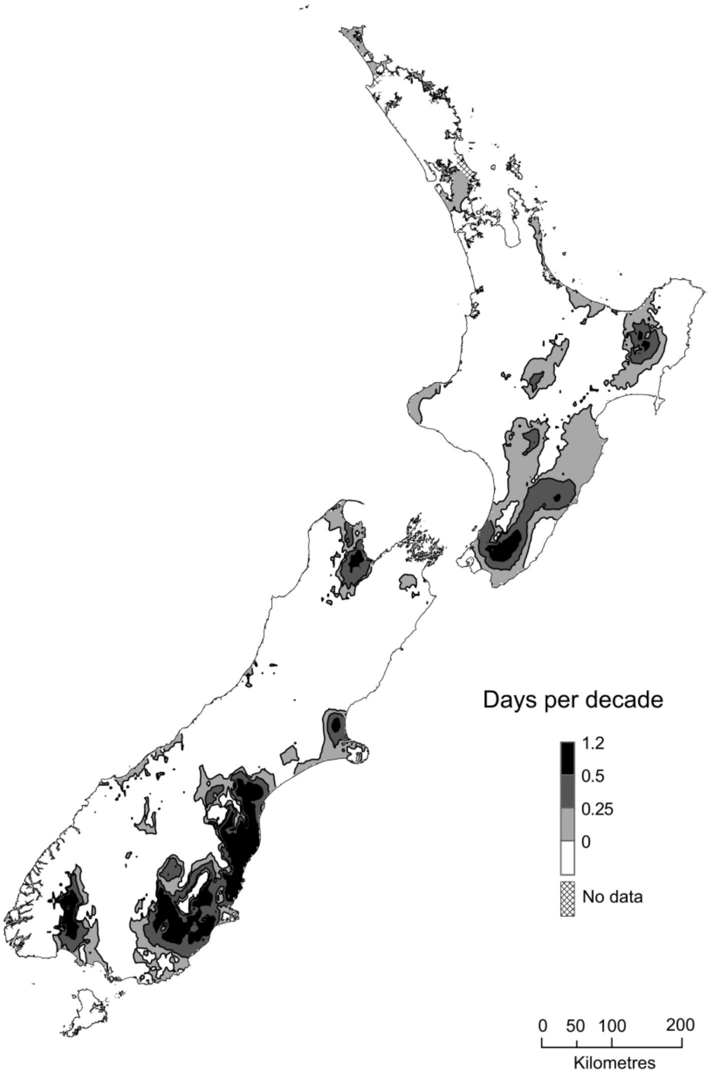


Figure 9: Location of areas showing an increase in annual screen frost frequency over New Zealand 1972 to 2008, modified after Clark and Sturman (2009) (Sturman and Quénol 2013).

In contrast to the increasing trend in frost frequency over recent decades noted by Sturman and Quénol (2013), downscaling the effects of IPCC scenarios to the regional scale resulted in a decreasing trend of frost occurrence over the medium to longer term, as illustrated in the maps shown in Figure 12. Projected medium and long term trends for the Marlborough region are different from those observed over the last fifty years or so, with a reduction of the number of annual and spring frost days expected by 2030-2049. The maps suggest that the main factor affecting variability in the occurrence of frost is the distance to the ocean, combined with the orography, factors that are well recognised to control the spatial variability of temperature. As shown in Figure 12, the sea-land gradient is quite sharp for the 1980-1999 period, resulting in a rapid increase in frost occurrence with distance inland, as well as at higher altitude, while projected maps for the two future periods suggest a reduction in both the sea-land gradient and the orographic effect.

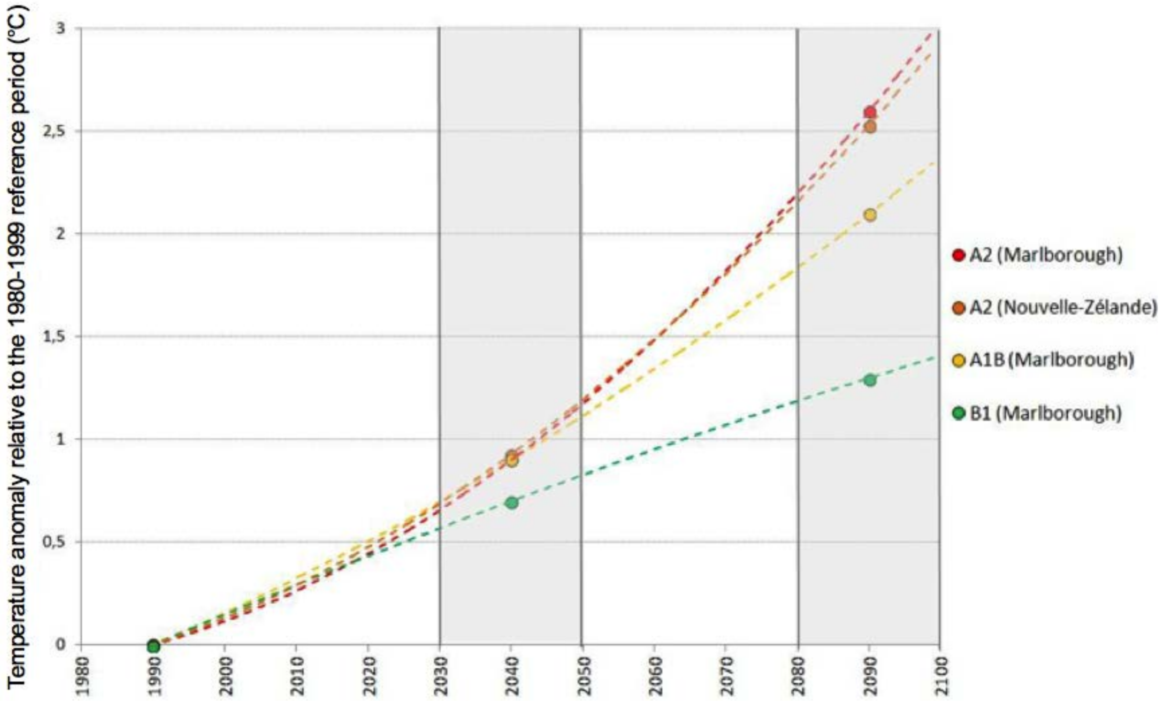


Figure 10: Mean annual temperature anomalies projected for 2030-2049 and 2080-2099 in relation to the reference period 1980-1999 for different IPCC SRES scenarios. The curves are polynomial trends that simply provide a better visualization of temperature increase throughout the period between 1980 and 2100. Note: only the A2 scenario increase for the whole of New Zealand is displayed on the graph, as the A1B and B1 increases are similar to the Marlborough region ones (Philippe et al. 2013).

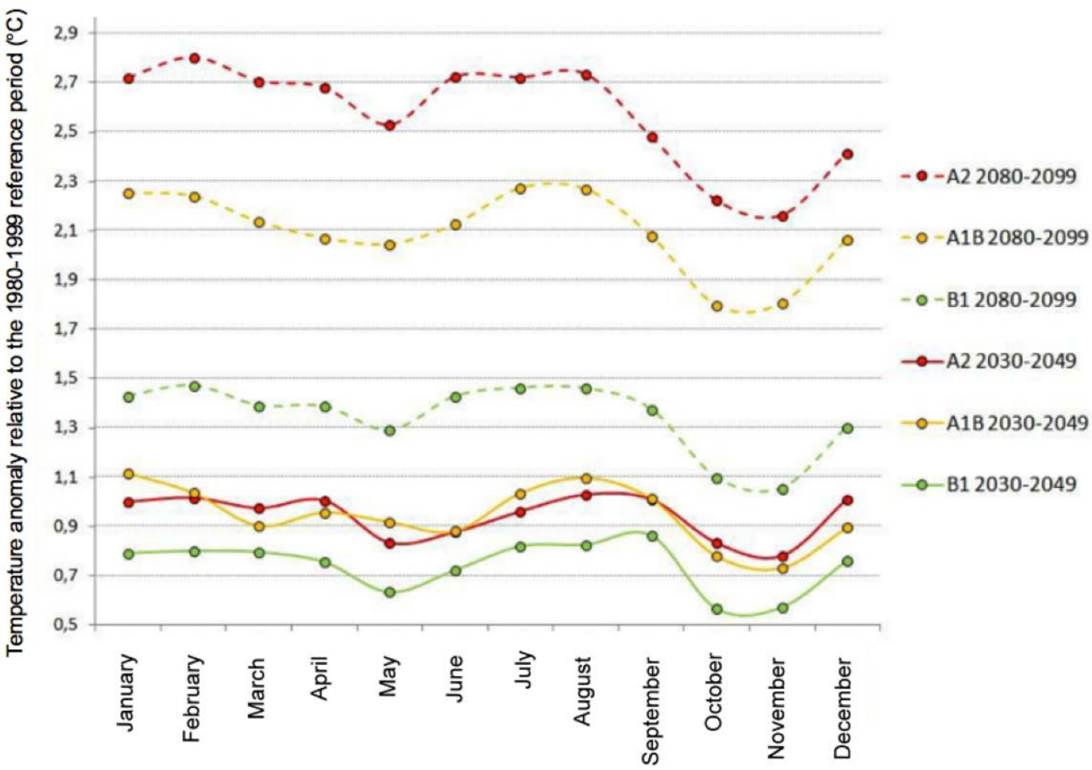


Figure 11: Average monthly temperature anomalies relative to the 1980-1999 reference period, calculated for the three IPCC scenarios and the two future periods (2030-2049 and 2080-2099) across the Marlborough region (Philippe et al. 2013).

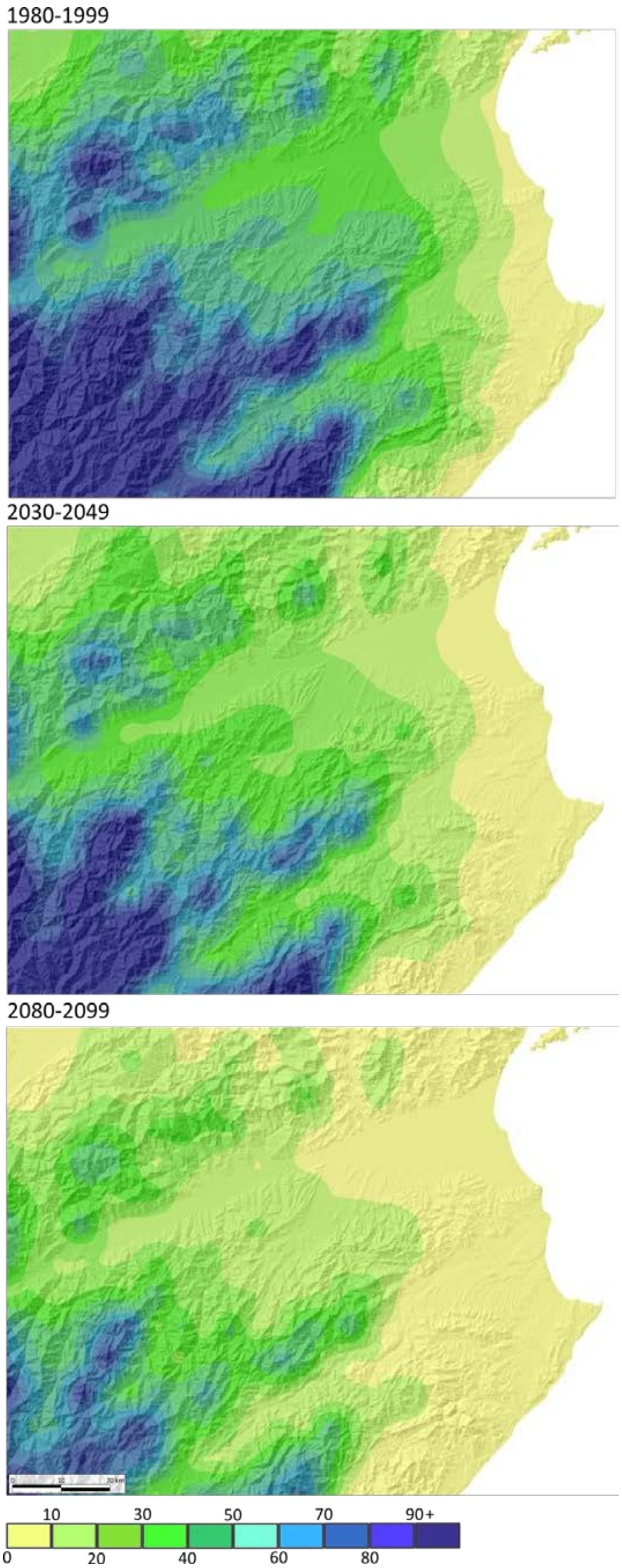


Figure 12: Mean annual number of days of frost obtained for the reference period 1980-1999, and projected for 2030-2049 and 2080-2099 according to the IPCC A1B SRES scenario over the Marlborough region (maps constructed using ArcMap and a Kriging method from 300 grid points) (Philippe et al. 2013).

Evaluation of bioclimatic indices over the period 1980-1999 for the Marlborough region has revealed the uncertainty associated with the identification of different types of wine-growing climate (Philippe et al. 2013). It is therefore not possible to interpret bioclimatic maps too precisely and definitively, as the boundary between two types of wine climate can vary significantly, especially in areas of the region where the terrain is particularly complex. In spite of these uncertainties, future changes projected for the various bioclimatic indices seem sensitive enough to conclude that a change in the types of viticultural climate should be observed as early as 2030-2049 across the region based on IPCC SRES projections. In the medium term, the 'cool' climate type of the Huglin index should cover all of the Wairau Valley, as well as the downstream part of the Awatere Valley (see Figures 2 and 13). In the long term, these two areas should be characterized by the ‘temperate’ type of climate as defined by Huglin and represented by the current climate of Bordeaux in France. According to predicted changes in the Winkler index, the downstream (coastal) sections of the two major river valleys may shift from region I to region II (equivalent to Hawkes Bay, Nappa and Bordeaux today). In the long term, the climate characteristics of Winkler’s region II should extend upstream, while small sections along the coast could switch to region III (similar to the south of France today) (Figure 13). Finally, according to the cool nights index, the very cool nights (categories 3 and 4) which are currently found at the Cape Campbell station should progressively cover most of the area covered by vineyards in the two main valleys, with a narrow coastal strip covered by the slightly warmer category 5 (Figure 13). The possible evolution of wine-growing climates may induce changes in grapevine development phases (flowering and véraison) and consequently modify wine quality. As a result of such climate modification, bioclimatic indices currently used might have to be adapted in the future in order to better represent regional climate characteristics. Observed changes in values of climate indices reflect recorded shifts in grape phenology, and many preceding studies have characterised increased temperatures and advances in phenology, maturity or ripening as a result under current and future climate conditions (Jones and Davis 2000, Duchêne and Schneider 2005, Jones 2006, Webb et al. 2007, Caffarra and Eccel 2011, Sadras and Petrie 2011a).

There is currently significant uncertainty associated with ability of global climate models to accurately predict future conditions at the regional (< 100s km) and local scale (< 10s km). However, as the ability of the science community to both model future climate at the larger scale and to downscale future projections to the local scale, current phenological techniques will still be valid for assessing the influence of climate variations on grapevine response. A recent international study has suggested that, based on current projections of global climate change, New Zealand vineyard regions are likely to be some of the most sustainable in the world (Hannah et al. 2013).

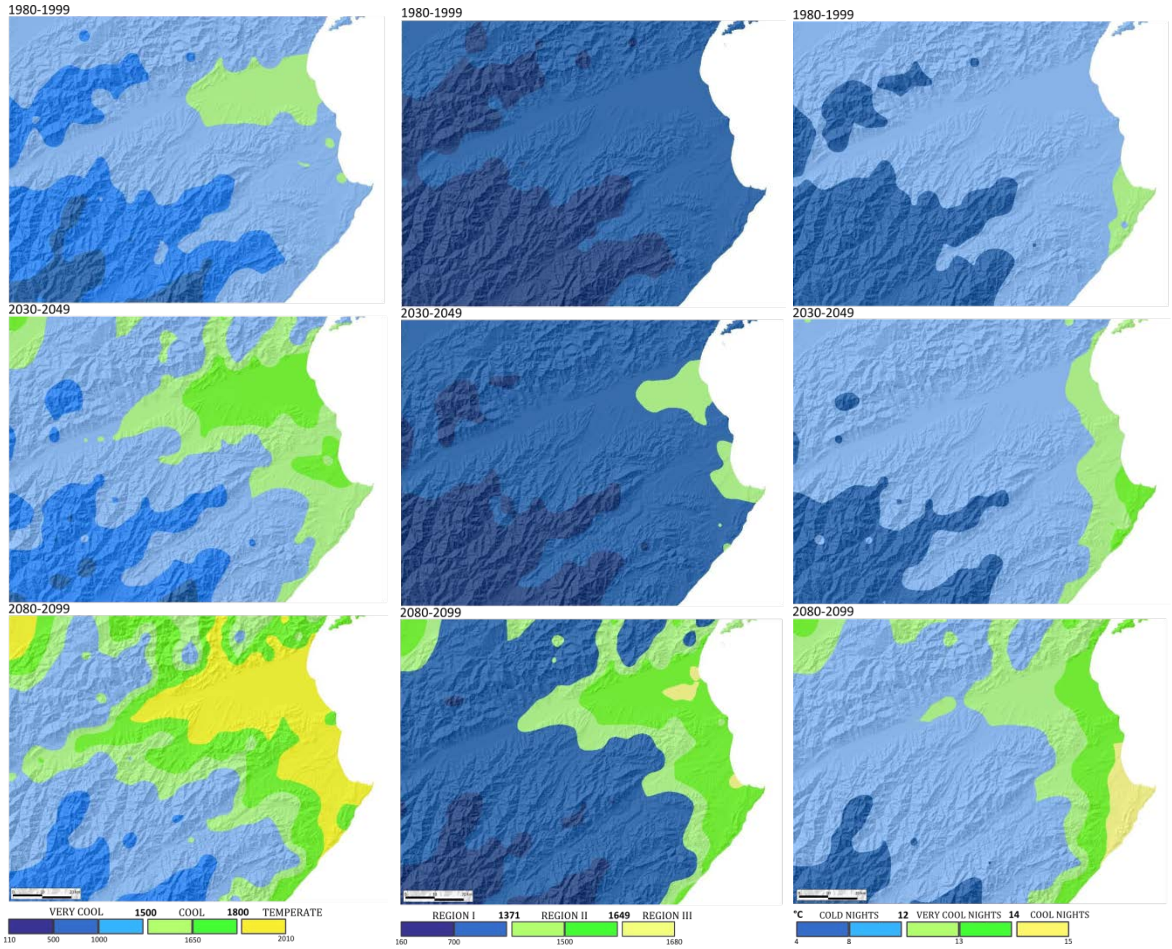


Figure 13: (Left) Huglin index values, **(Middle)** Winkler index values, and **(Right)** cool nights index values for the Marlborough region modelled over the reference period 1980-1999 and expected for 2030-2049 and 2080-2099, according to the IPCC A1B SRES scenario (maps created using ArcMap and a Kriging method from 300 grid points). Each colour defined in the scale refers to a Climate type (Huglin), Region (Winkler) or Category (Cool nights index) with the dark blue colour representing coldest areas and yellow representing warmest areas (Philippe et al. 2013).

2.2 EFFECTS OF RECENT DECADAL CHANGES IN ATMOSPHERIC CIRCULATION ON AIR TEMPERATURE

Sturman and Quénol (2013) investigated the impact of global warming on viticulture using the major vineyard regions of New Zealand as a case study to illustrate regional disparities in climate change impacts resulting from downscale effects of larger scale atmospheric circulation. Recent trends in air temperature in New Zealand vineyard areas were investigated, and trends in Marlborough since 1941 showed an increase in temperature range, with both rising maximum temperatures and declining minimum temperatures, but no change in the annual mean (Figure 14). More hot days and frosts are of concern to viticulturalists, and this trend not only differs from other major vineyard areas (Figure 15), but also occurs at other sites in eastern parts of the country (e.g. Christchurch – Figure 15b), as also identified by Clark and Sturman (2009). The increased temperature range (that can lead to earlier budburst and increased frost damage) and frequency of frost at Blenheim (Figures 16 and 17) is of particular concern to viticulture, as it represents an increased climate risk factor and is contrary to the publicly expected outcome of global warming. An increase in mean temperature is expected to result in earlier budburst and therefore increase the risk of any damage in the event of late frosts. Such frosts will still occur whether there is warming or not, as factors that determine their occurrence include such things as daylength, which will remain unchanged under a warmer climate regime.

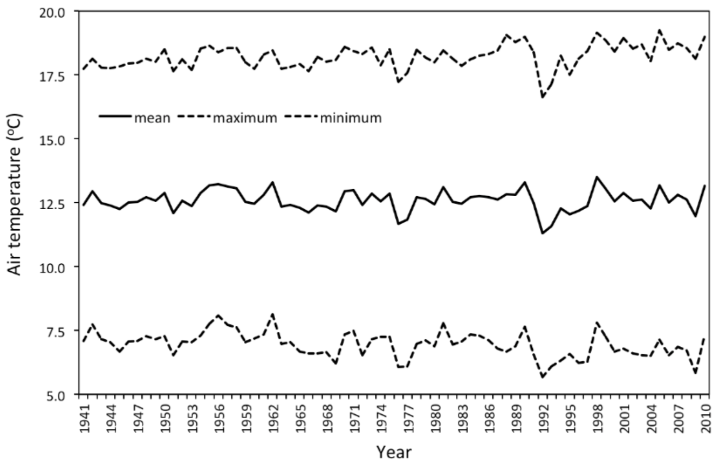
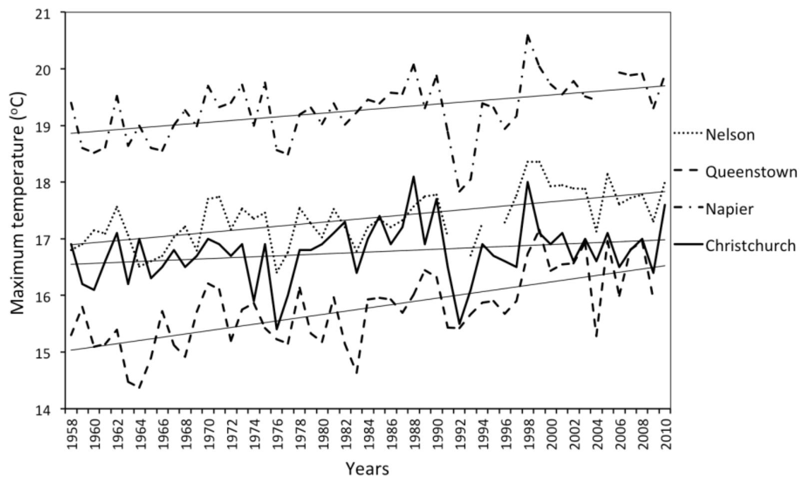


Figure 14: Annual mean daily maximum, mean and minimum temperatures for Blenheim airport from 1941 to 2010 (original data from NIWA) (Sturman and Quénol 2013).

a)



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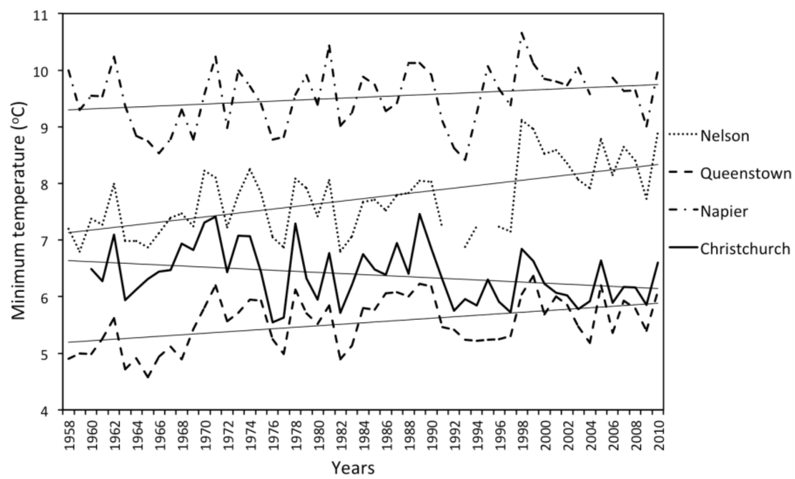


Figure 15: Annual mean daily (a) maximum and (b) minimum temperatures at Napier, Nelson, Christchurch and Queenstown (original data from NIWA) (Sturman and Quénol 2013).

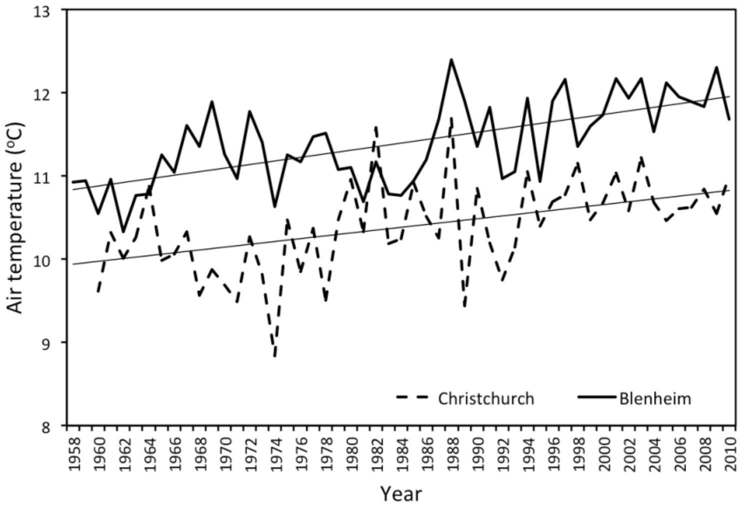


Figure 16: Annual mean daily temperature range at Blenheim and Christchurch airports between 1958 and 2010 (original data from NIWA) (Sturman and Quénol 2013).

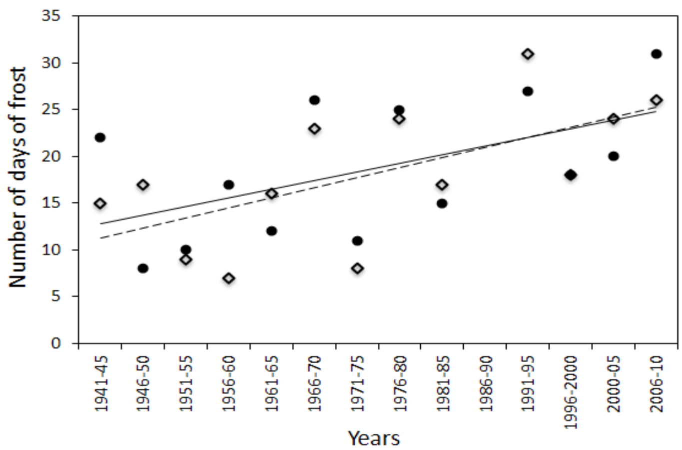
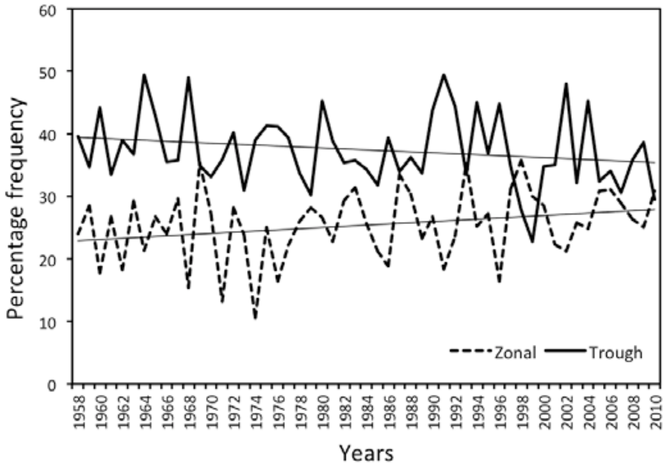


Figure 17: Trend in the number of days of spring (September to November) and autumn (March to May) frost per 5-year period at Blenheim airport (original data from NIWA). Data for 1986–1990 are missing, while the value for 1991–1995 is an underestimate, as the data are incomplete. Linear trends for spring (open symbols) and autumn (solid symbols) are indicated by the dashed and solid lines, respectively (Sturman and Quénol 2013).

The relationship between changes in atmospheric circulation over New Zealand and observed trends in temperature and frost occurrence at Blenheim was investigated using the Kidson weather type classification for the period 1958–2010 and the Trenberth M1 index (Sturman and Quénol 2013). The increased temperature range observed at Blenheim appears to be associated with more frequent clear skies along the east coast of the country, resulting from changes in weather patterns (more frequent anticyclones, fewer low-pressure systems, increased zonal and southerly flow – Figures 18 and 19). These changes in weather patterns were shown to be closely linked to larger scale changes in atmospheric circulation via the Southern Annular Mode (SAM) (Figure 20) and Southern Oscillation. The results show that significant regional variations in the impact of global warming can occur over areas of complex terrain such as New Zealand. Observed differences in local temperature and frost trends can be caused by the interaction of changing weather systems with mountainous terrain. These changing weather systems themselves are seen to be the result of major shifts in the larger scale atmospheric circulation. These conclusions are important for assessing possible impacts of future climate change on viticulture in regions of complex terrain and in developing appropriate adaptation strategies for agriculture.

a)



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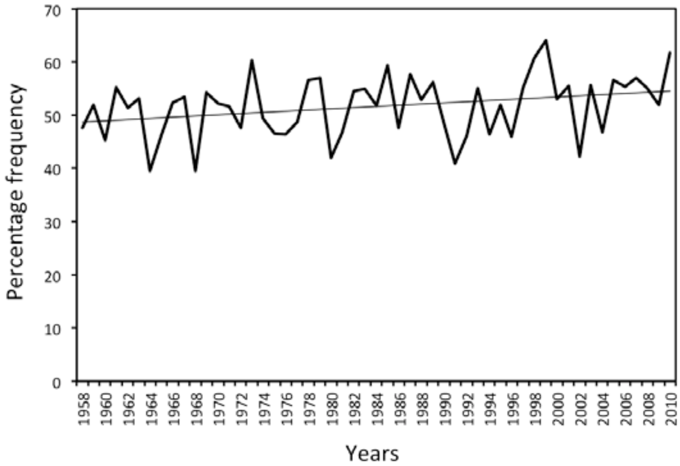

Figure 18: Trends in the percentage frequency per annum of (a) ‘zonal’ and ‘trough’ weather types, and (b) highs and ridges over the New Zealand region, between 1958 and 2010 (Sturman and Quénol 2013).

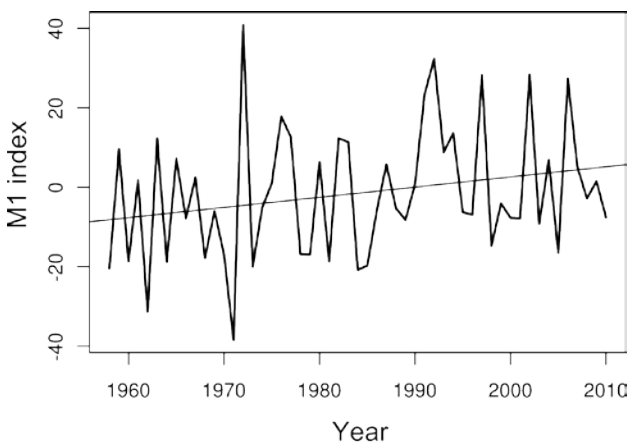

Figure 19: Time series of the M1 index between 1958 and 2010 (data obtained from NIWA) (Sturman and Quénol 2013).

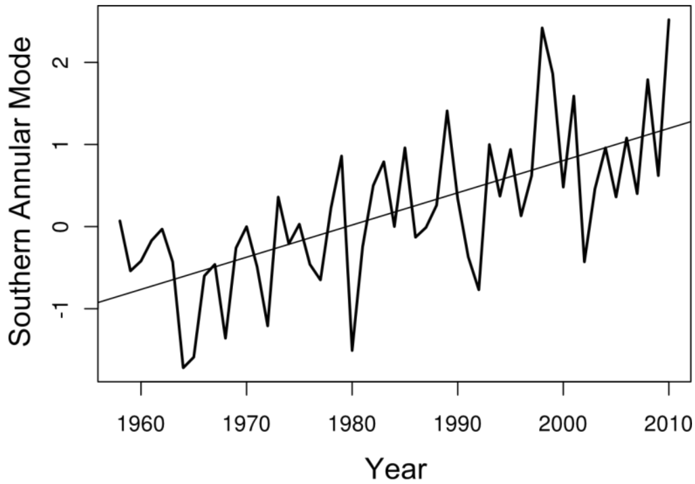

Figure 20: Time series of the Southern Annular Mode between 1958 and 2010 (data obtained from http://www.lasg.ac.cn/staff/ljp/data-NAM-SAM-NAO/SAM(AAO).htm) (Sturman and Quénol 2013).

Having completed an initial investigation into the impact of changes in atmospheric circulation patterns on regional weather patterns and temperature variations in New Zealand's vineyard regions (Sturman and Quénol 2013), a more intensive analysis of temperature variations across the country was undertaken using many more sites, focusing on vineyard areas, for which measurements were available between 1945 and the present day. The objective of this subsequent analysis was to assess the extent to which the increase in daily temperature range observed at Blenheim and Christchurch was replicated at other sites (in or close to vineyard areas) around the country, and to attempt to explain any observed regional variations. Average daily maximum, minimum and mean temperature data for each year since 1945 were therefore obtained from the National Climate Database for 340 stations across New Zealand. As many stations did not have data covering the whole time period, the data were organised into decades and the stations that experienced an increasing temperature range over each decade were identified and located on New Zealand base maps. Overlapping decades (starting every five years – i.e. in 1945, 1950, 1955, 1960, etc.) were used to maximise the amount of data available for analysis.

The analysis showed that there have been an increasing number of weather stations at which the temperature range has increased since the 1940s, although this is partly due to the increase in total number of available stations (Figure 21). When the number of such stations is expressed as a percentage of those available, there appears to be three distinct periods. Up to 1960, there seems to have been a significant percentage (about 50%) of stations experiencing an increased temperature range, while between about 1960 and 1979 this dropped to around 30%. There was some variability in the 1980s, but since about 1990 there has been an increase in the percentage frequency (about 60%) of stations recording an increased temperature range, peaking at around 80% of the stations analysed between 2010 and 2012 (Figure 21). Figure 22 indicates that there was a significant number of stations in vineyard regions of New Zealand showing an increase in temperature range since 2000.

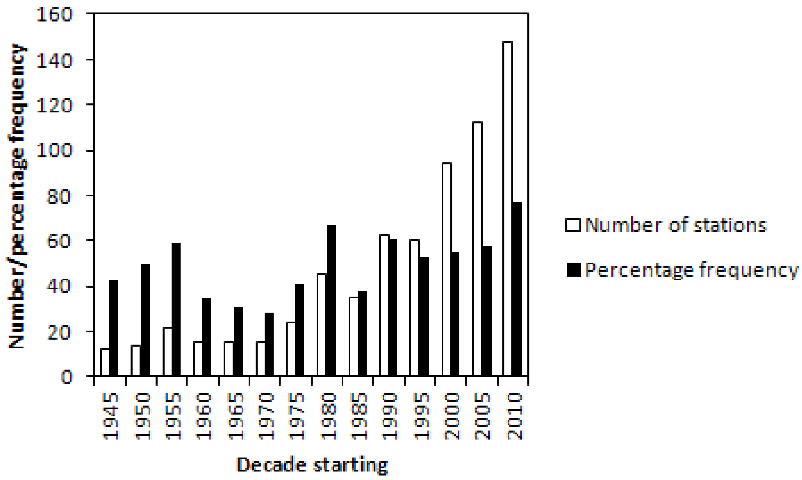

Figure 21: The number and percentage frequency of weather stations experiencing an increased temperature range over overlapping ten year periods starting in the year indicated (only three years for the last period).

When examining the different types of mean temperature change associated with sites experiencing an increased temperature range, the results showed an interesting change in the nature of these temperature trends from the 1980s and 1990s, when the increasing temperature range was associated with an overall warming trend (i.e. mean annual temperatures were increasing over time), to the past decade, when it appears that the increasing temperature range was associated with cooling at many sites (i.e. mean annual temperatures were decreasing over time).

This intensive analysis of temperature trends has confirmed that although the 7- and 11-station national mean annual temperature time series for 1910 to 2010 published by NIWA show a warming trend for New Zealand (https://www.niwa.co.nz/our-science/climate/information-and-resources/nz-temp-record/seven-station-series-temperature-data), there is significant variation in the nature of temperature variations in key vineyard areas across the country and between different decades. In particular, there appears to have been an increase in the daily temperature range at many sites over recent decades, and this was initially associated with a warming trend through the 1980s and 1990s (that is, an increased diurnal thermal amplitude due to a higher maximum), but that recently the mean annual temperature at many of these sites has started to decrease or remain constant. The trends in mean growing season temperature shown for sites in New Zealand’s main vineyard regions are in line with recently published data showing a levelling off or slight decrease of temperatures globally (see Figures 23 and 24). The strong temperature increase seen at most sites during the 1990s has therefore not been maintained through the 2000s. A key feature shown in Figure 23 is the general reduction in interannual temperature variation, which should be helpful to the wine industry as it provides some consistency in growing conditions and presumably wine quality from year to year.

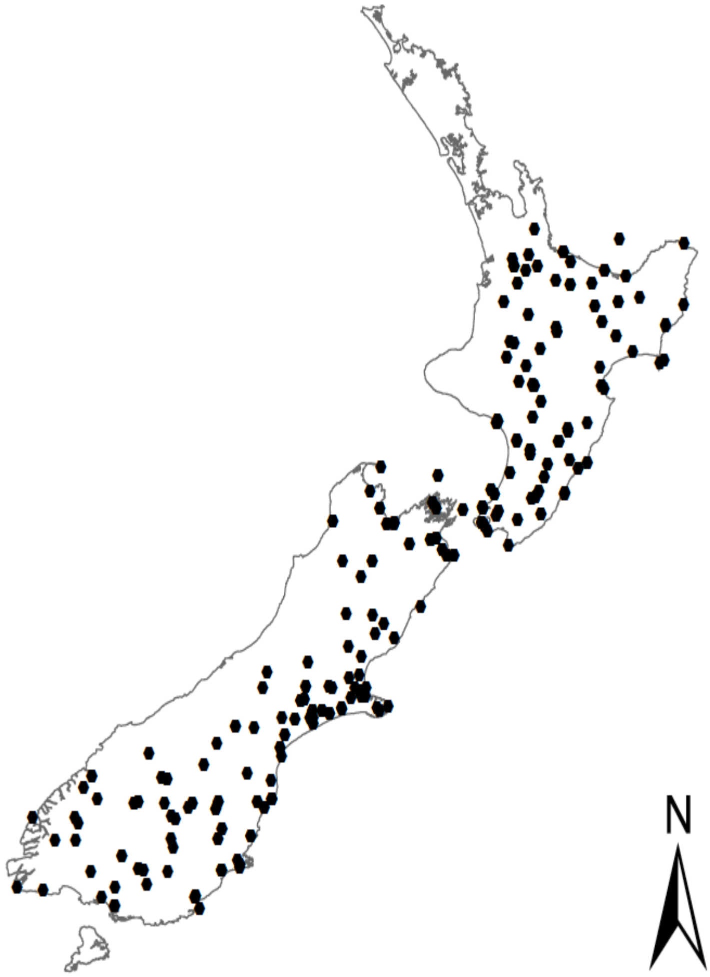

Figure 22: Location of weather stations in New Zealand experiencing an increased temperature range over the ten-year period starting in 2000.

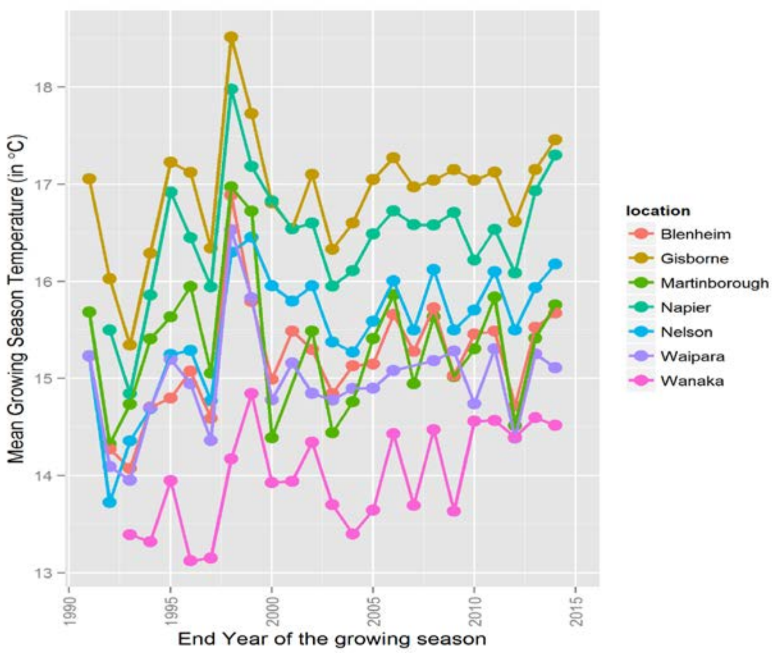

Figure 23: Mean growing season temperature (September to May) for sites in the main vineyard regions of New Zealand from the 1990-91 to the 2013-14 growing season.

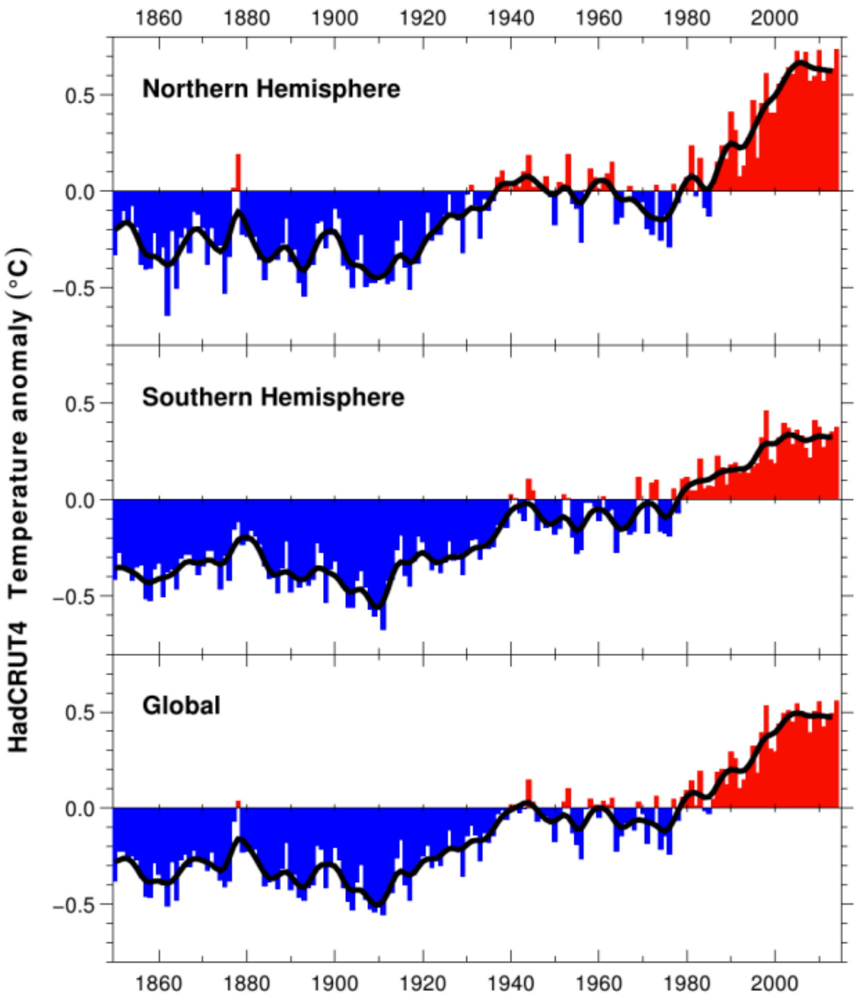

Figure 24: Trends in global and hemispheric air temperatures up to November 2014 (from http://www.cru.uea.ac.uk/cru/data/temperature/HadCRUT4.png).

These conclusions help to confirm the results provided by Sturman and Quénol (2013), who also found that mean annual temperatures at weather stations in vineyard areas have tended to decline since about 1998 (this is evident in Figure 15), over which time temperature range has increased at a number of vineyard sites (such as Blenheim and Christchurch). These results are supported by other researchers, including Dean and Stott (2009) who have also identified an increase in occurrence of southerly flow across the New Zealand region over recent decades which appears to have offset the impact of global warming on the country.

Much of the variation in temperature regimes in vineyard areas can be explained as due to shifts in the major features of the atmospheric circulation of the Southern Hemisphere, which in turn have affected the frequency of the most important weather systems affecting New Zealand (Sturman and Quénol 2013). The increased frequency of anticyclones and decreased numbers of lows appear to be key factors together with increased frequency of southerly winds, although their interaction with New Zealand's complex terrain has created regional variations in temperature response. Further analysis and modelling of atmospheric processes from hemispheric to local scales, and their coupling with phenological and crops models, will help to develop new knowledge and a set of tools to assist vineyard owners in different regions to adapt to future climate variability.

2.3 OVERALL SUMMARY OF CLIMATE CHANGE EFFECTS

Significant differences have been discovered in the temperature trends observed in different vineyard regions of New Zealand. The most economically important vineyard region, Marlborough, appears to have experienced an increase in the daily temperature range since the 1940s so that the grapevines are more frequently exposed to both higher and lower temperatures over recent decades (Sturman and Quénol 2013). This is also associated with an increased frequency of frosts. These temperature trends appear to be the result of shifts in the main atmospheric circulation features of the Southern Hemisphere causing a change in the occurrence of the different weather systems that normally affect the New Zealand region (Sturman and Quénol 2013). In particular, there seems to have been an increase in anticyclones (high pressure systems) over recent decades, with a corresponding decrease in low pressure occurrence. Anticyclones tend to produce clear skies and light winds, which result in higher daytime temperatures and lower night-time temperatures (i.e. an increased daily temperature range). There has also been an increase in westerly and southerly flow over the country associated with cooling that appears to have offset the impact of any global warming trend in some parts of the country. It is evident from these results that New Zealand's complex terrain has caused regional and local variations in the way in which climate has changed over recent years, as a result of the way in which the changing weather systems interact with the terrain.

Further investigation is therefore planned to identify the nature of these local variations, particularly in relation to observed temperature trends in different vineyard regions. These results have also provided background knowledge of recent temperature variations in vineyard regions from which coupled atmospheric and phenological/crop models are being evaluated to help the wine industry adapt to future changes in climate.