Ministry for Primary Industries
Manatū Ahu Matua

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

Part 2

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Contents

Page

3. Weather/climate model application

The WRF mesoscale meteorological model is run operationally on the University of Canterbury's high performance computing facility. In this project, a series of model runs were conducted for the Marlborough region to select the most appropriate parameterisation schemes for this specific application. After the tests were completed, the model was then set up to run on an operational basis during the grapevine growing season, providing daily weather predictions for two vineyard regions (Marlborough and Waipara) in the form of hourly maps of forecast winds and temperature, as well as daily maps of accumulated bioclimatic indices. A prototype web site was established early in the 2013-14 growing season to display the results in the form of maps and graphs, and the process of model validation has been running in parallel since this time.

3.1 VALIDATION OF THE HIGH-RESOLUTION WEATHER AND CLIMATE MODEL IN THE MARLBOROUGH VINEYARD REGION USING THE ENHANCED DATA NETWORK

Temperature is the main variable of interest in relation to impacts on viticulture, so the model validation process focused primarily on assessing the ability of the WRF model to reproduce mean daily temperature over the Marlborough region. Figure 25 and Table 5 provide a summary of the validation statistics, which shows that the WRF model had a relatively small cold bias during the 2013-14 growing season, but that the model simulations were highly correlated with observations from the automatic weather station network (see Figure 6 for the locations of sites mentioned in Table 5 and the following text). The index of agreement is a internationally recognised measure of model performance (Willmott 1982, 1985) that indicates that the WRF model was able to accurately reproduce mean daily temperatures at most sites in the Marlborough region. The cold bias is reasonably uniform (between about -0.6 to -1.6°C) in the more Wairau Valley but appears to increase with distance inland in the Awatere Valley. Bandalero stands out as the site for which WRF has the coldest bias (-2.18°C) – that is, the model under-predicts the temperature at this site. This is likely to be the result of the complex terrain surrounding this site, which is located at a narrow constriction in the Wairau Valley. At 1 km resolution, WRF is unable to fully represent the effects of this constriction on atmospheric processes, such as the acceleration of cold air drainage through the valley at this point. Jet-like structures created by narrowing of the valley would increase mechanical mixing of air close to the surface and cause the observed temperature to be higher than at other valley-floor locations. The effect of model resolution on the ability to represent fine scale variations in meteorology was previously acknowledged by Bonnardot and Cautenet (2009) in a similar modelling study in South Africa. In contrast, the most coastal site (Blind River Reserve) shows a slight warm bias (0.49°C). This site is so close to the coastline that, in this case, the effect of WRF model resolution (1 km) appears to be that the grid cell surrounding the site is considered to have the surface characteristics of the sea. This would mean that the bias is likely to vary seasonally in response to seasonal changes in the temperature difference between land and sea. Figure 26 shows that this is indeed the case, with this site showing a more positive bias early and late in the season, with a negative bias in December (mid-season). Overall, the monthly analysis of model bias shows that the WRF model simulations of mean daily air temperature appear to be closer to observations during the early and later parts of the season, with the greatest negative bias at all sites occurring during December (Figure 26). This corresponds with a general tendency for the WRF model to produce a lower amplitude in diurnal temperature variations than is actually observed at most sites (extremes are moderated). This appears to translate to a lower seasonal amplitude in temperature, which would mean that WRF simulated temperatures would be closer to observed values during the intermediate seasons (i.e. in September and March, as shown in Figure 26).

Table 5: Validation statistics for mean daily air temperature for the WRF model runs, September 2013-April 2014 (BR Reserve = Blind River Reserve). RMSE = root mean square error, R = Pearson's correlation coefficient, IOA = Index of Agreement (Willmott 1982, 1985), mean bias = mean modelled minus mean observed.

Station	Mean Obs	Mean Model	St. Dev. Obs	St. Dev. Model	RMSE	R	IoA	Mean bias
Bandalero	14.73	12.54	3.19	2.70	3.04	0.75	0.76	-2.18
Ben Morven	15.03	14.38	3.14	2.65	2.13	0.77	0.85	-0.64
Blind River	14.71	14.03	3.14	2.33	2.27	0.72	0.82	-0.68
Booker	14.81	13.92	3.11	2.60	2.16	0.77	0.85	-0.89
BR Reserve	14.87	15.35	3.17	2.01	2.40	0.67	0.77	0.49
Lower Wairau	15.61	14.37	2.76	2.44	2.08	0.70	0.80	-1.24
Mt. Riley	15.53	13.88	3.03	2.54	2.26	0.78	0.83	-1.65
Omaka Valley	14.96	14.06	3.14	2.62	2.19	0.77	0.85	-0.89
Seddon Vineyard	14.12	12.95	3.43	2.61	2.82	0.72	0.78	-1.17
Taylor's Pass	15.41	13.55	3.06	2.43	2.79	0.60	0.70	-1.86
Waihopai	14.52	13.83	3.29	2.65	2.24	0.76	0.85	-0.69

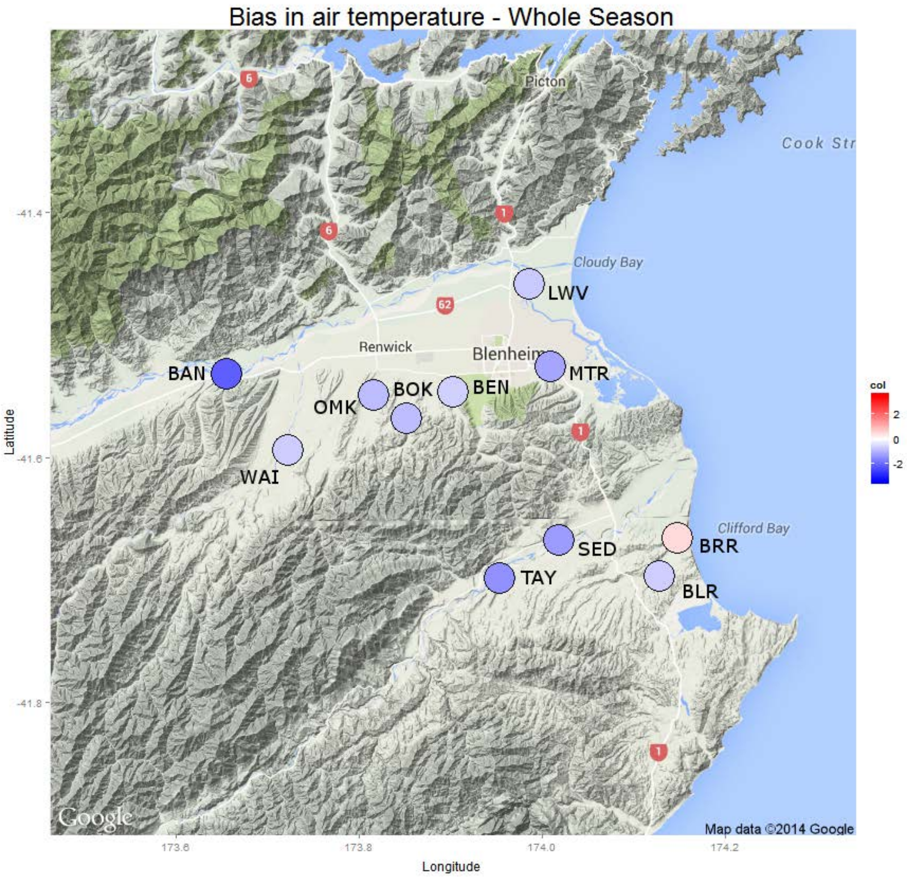


Figure 25: Mean daily air temperature bias for the WRF model during the whole growing season September 2013 to April 2014. Site names: BAN = Bandalero, WAI = Waihopai Valley, OMK = Omaka Valley, BOK = Booker, BEN = Ben Morven, LWV = Lower Wairau Valley, MTR = Mt. Riley, TAY = Taylor's Pass, SED = Seddon Vineyard, BLR = Blind River and BRR = Blind River Reserve.

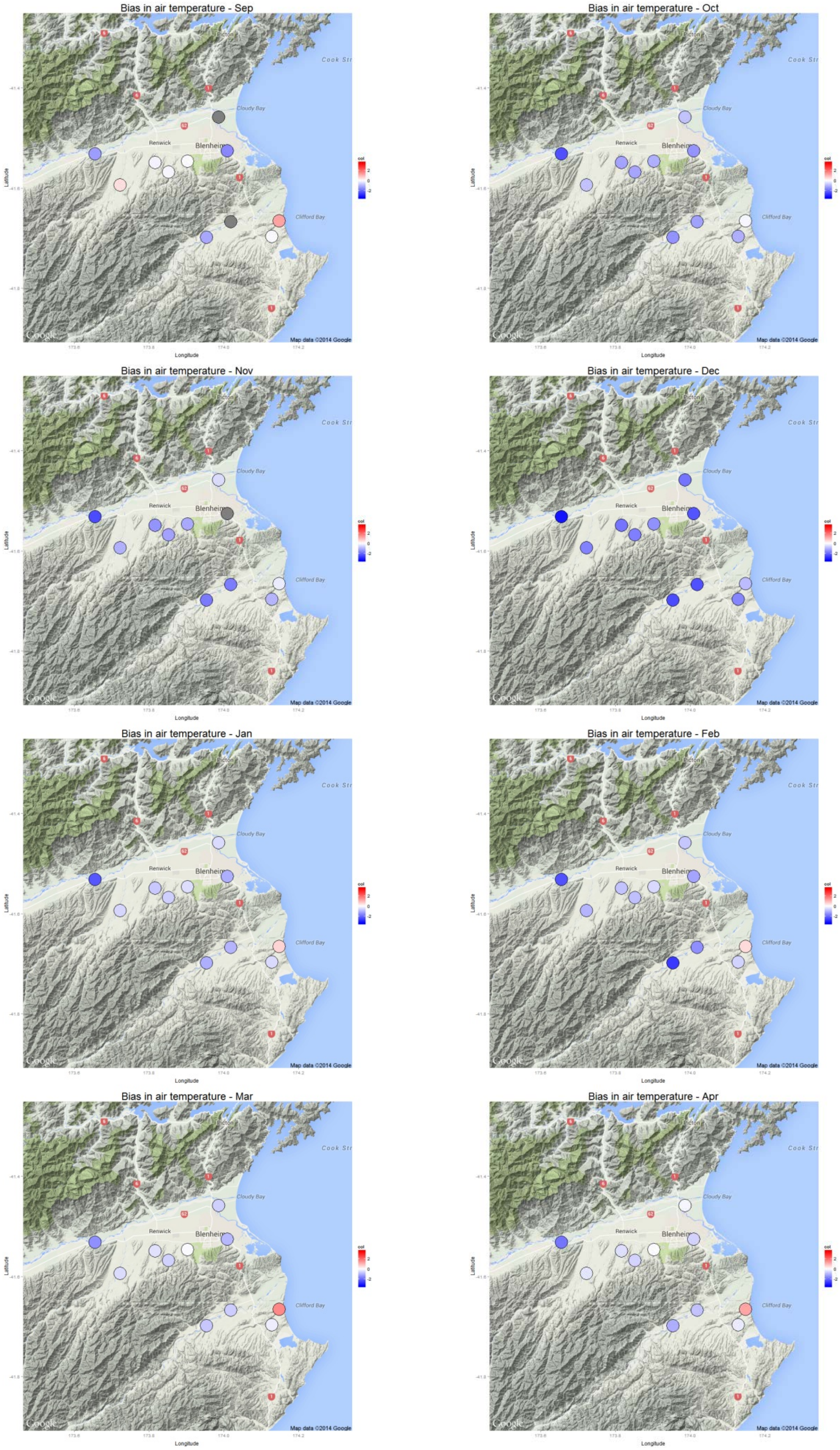


Figure 26: Mean daily air temperature bias for the WRF model during individual months during the growing season September 2013 to April 2014 (site names in Figure 25).

3.2 HIGH-RESOLUTION WEATHER AND CLIMATE MAPPING OF THE MARLBOROUGH VINEYARD REGION AT A RANGE OF TIME SCALES

The WRF model has been running operationally twice daily since early in the 2013-2014 growing season, providing hourly forecast maps over a 24-hour period of near-surface temperature and wind (Figure 27) which are automatically uploaded to the project web site (www.wineclimate.co.nz). These maps are designed to provide local wine-producers with short-term weather predictions for the local area for use in day-to-day vineyard management.

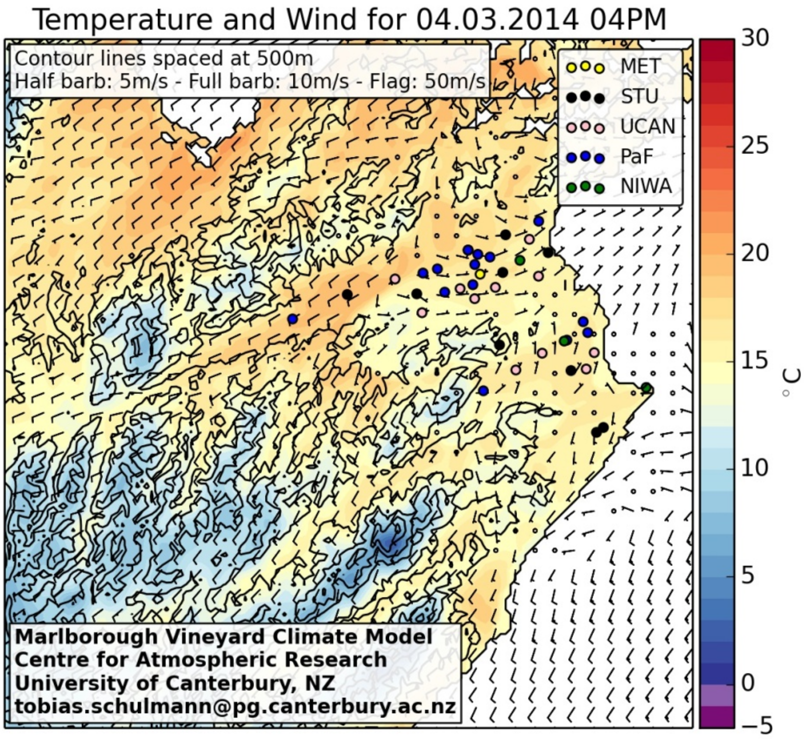


Figure 27: Example of an operational output map of hourly temperature and wind from the Weather Research and Forecasting (WRF) model for the Marlborough region, 1600h on 4 March 2014.

It has also been possible to undertake a retrospective analysis of the hourly and daily weather variability experienced across the vineyard region by running the WRF model for the growing seasons since 2008-9. Figures 28, 29 and 30 provide maps of the key temperature variables of significance to viticulture (daily maximum, minimum and mean temperature) obtained at 1 km resolution from the WRF model across the region averaged for the six growing seasons from 2008-9 onwards, while inter-season variability is shown by the panels of six maps provided in Appendix A. The temperature maps show the strong influence of topography and distance from the sea on the spatial pattern. In the latter case, there is a narrow coastal strip within which temperatures are strongly affected by the sea. As a result, the highest mean maximum temperatures over the growing season tend to occur in the central sections of the Wairau and Awatere Valleys (see Figure 2 for locations), decreasing inland, towards the coast, and with altitude. The most important impression provided by the seasonal maps (Appendix A) is that the growing seasons since 2008-9 have experienced relatively small inter-seasonal variability compared to earlier periods. This is reflected by the temperature trends in all of New Zealand's vineyard regions, as shown earlier in Figure 23. Inter-seasonal variability in maximum temperatures is largely represented by only a subtle change to the spatial patterns. The growing seasons 2008-9 and 2012-13 show the largest areas of mean maximum temperatures > 20°C in the Wairau Valley, with 2011-12 and 2013-14 showing lower values (Figures A1d and f). Subtle changes are also evident in the gradient of maximum temperatures along the coastal strip, which is weakest in 2011-12 and 1012-13 (Figures A1d and e).

The spatial patterns of mean minimum temperature over the growing season shown in Figure A2 (Appendix A) also indicate the influence of topography and distance from sea, with coastal regions consistently experiencing higher values (> 12°C) while more inland parts of the Wairau Valley have lower values (< 8 or 9°C). Interestingly, the southeastern part of the region near Cape Campbell has consistently higher minimum temperatures (Figure 29 and Figure A2 in Appendix A). As for maximum temperatures, interseasonal variations in minimum temperature are subtle, with 2011-12 showing lower minimums across the region (Figure A2d), 2013-14 having higher average minimum temperatures (Figure A2f), with other years somewhere between and minor variations from year to year.

The spatial patterns of mean daily temperature obtained from the WRF model for the growing seasons since 2008-9 show a similar overall pattern to the other temperature maps, with temperatures generally > 15°C along the coast, with > 14°C over the bottoms of the two main valleys, and much of the rest of the area covered by vineyards experiencing > 13°C (Figure 30). Again, the inter-seasonal differences are small with slight changes in the extent of the region >14°C (Figure A3 in Appendix A), although in the cold growing season of 2011-12 the mean temperature is mostly less than 14°C across the whole region (Figure A3e), except for the southeastern corner which is predicted to have had >14°C (following the highway).

The temperature maps in Figures 28-30 and Appendix A suggest that the Wairau Valley to the north experiences greater temperature ranges than the Awatere Valley further south (see Figure 2 for locations), although they both have a similar mean temperature over the growing season. The least extreme temperature range appears to occur in the southeastern section, inland from Cape Campbell. These conclusions will be evaluated further through comparison of the WRF hourly meteorological data with observations from a range of weather stations across the region.

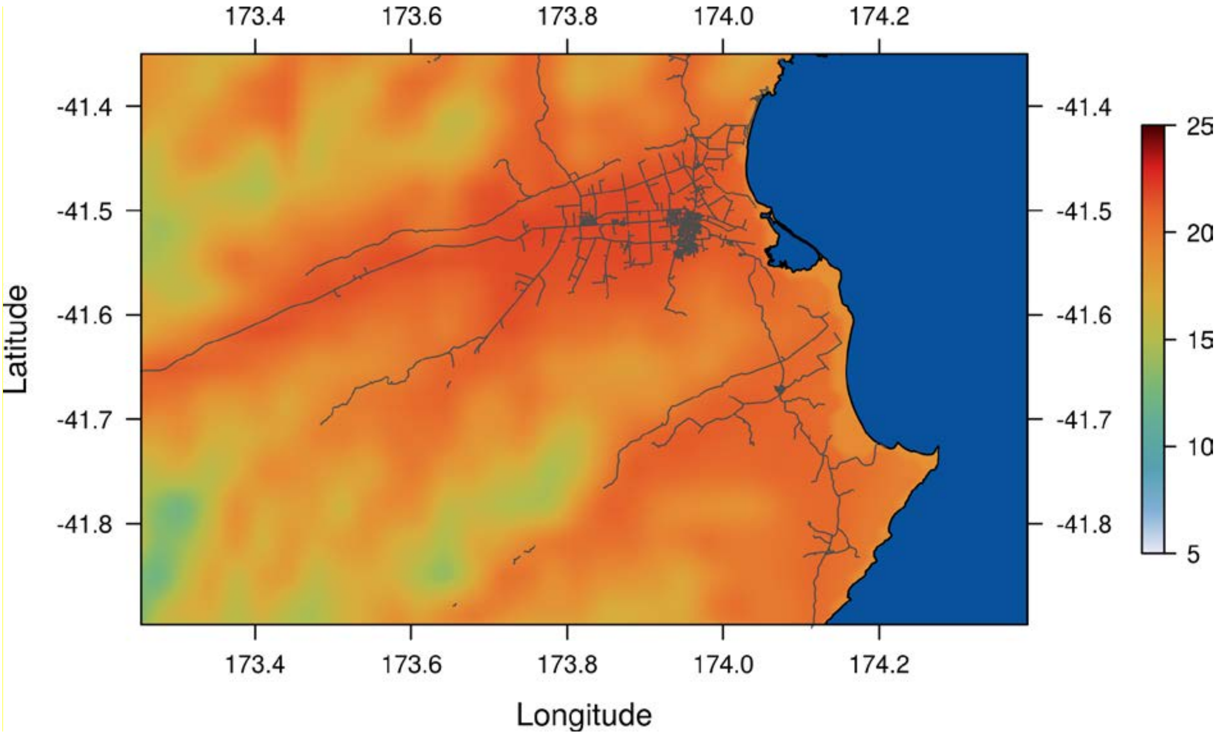


Figure 28: Map of daily average maximum temperature (ºC) averaged over the six growing seasons from 2008-9 to 2013-14 (1 October to 30 April) for the Marlborough region based on WRF output.

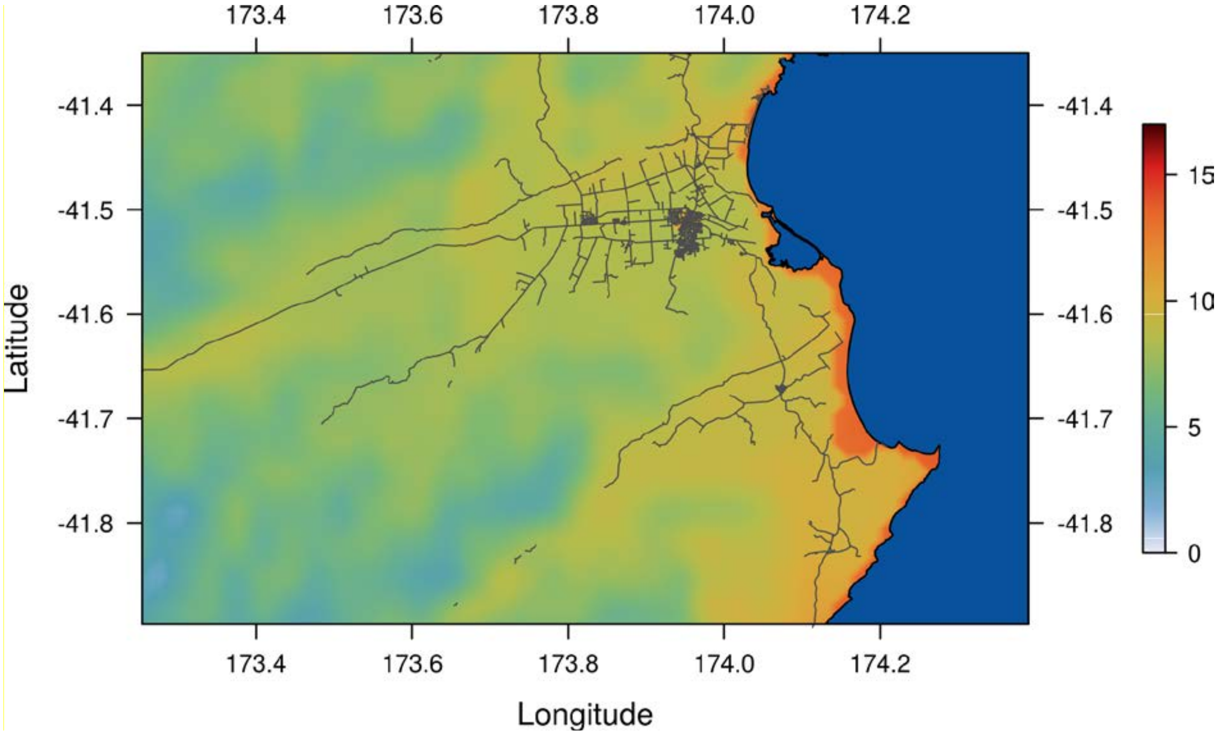


Figure 29: Map of daily average minimum temperature (ºC) averaged over the six growing seasons from 2008-9 to 2013-14 (1 October to 30 April) for the Marlborough region based on WRF output.

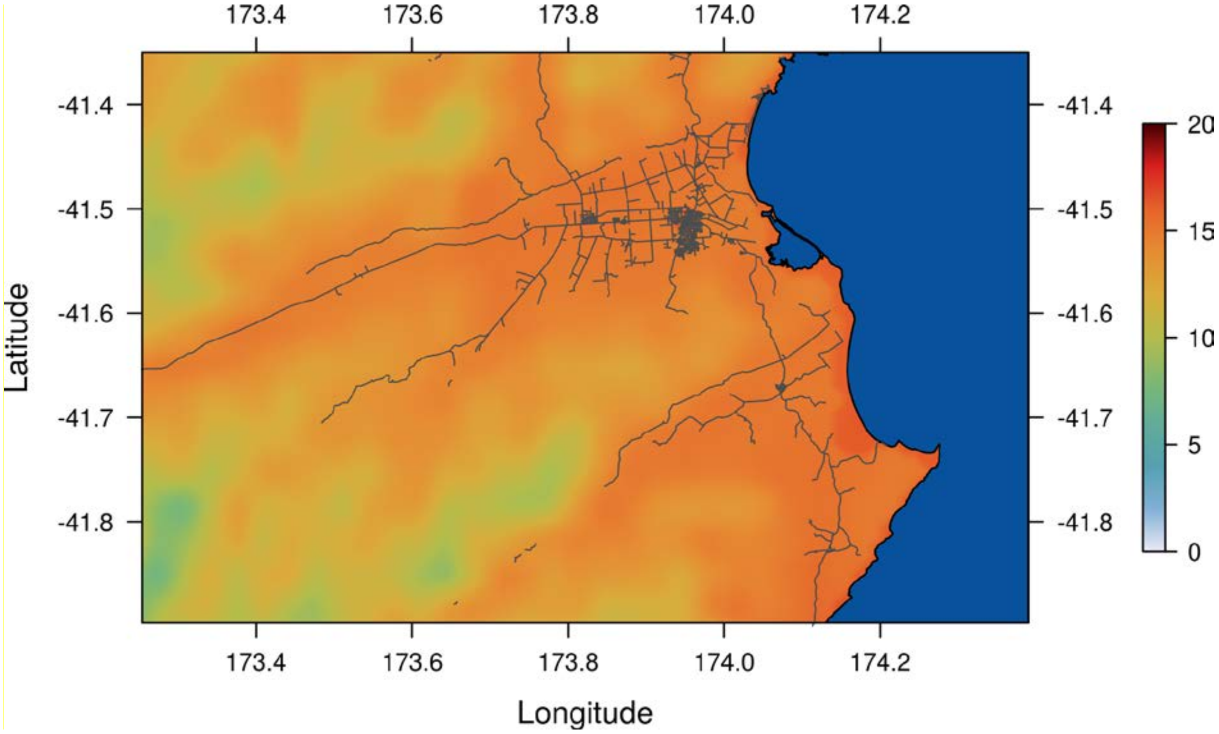


Figure 30: Map of growing season temperature (GST – ºC) averaged over the six growing seasons from 2008-9 to 2013-14 (1 October to 30 April) for the Marlborough region based on WRF output.

3.3 HIGH-RESOLUTION MAPPING OF BIOCLIMATIC INDICES IN THE MARLBOROUGH REGION BASED ON MODEL OUTPUT

In addition to providing maps of hourly wind and temperature for the Marlborough region based on WRF output data, the daily mean air temperatures derived from the hourly data are used to produce a 1 km resolution map of growing degree-days (GDDs) that is updated at the end of each day throughout the growing season. Figure 31 provides an example of a map produced during the 2014-15 growing season.

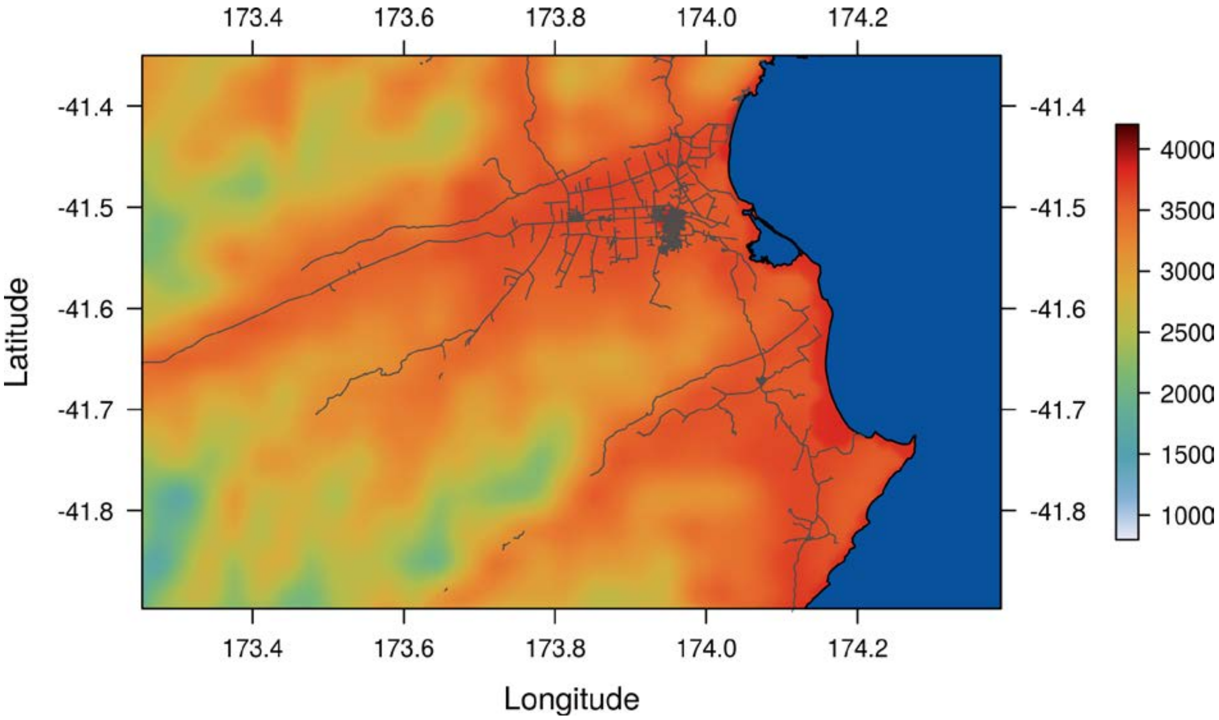


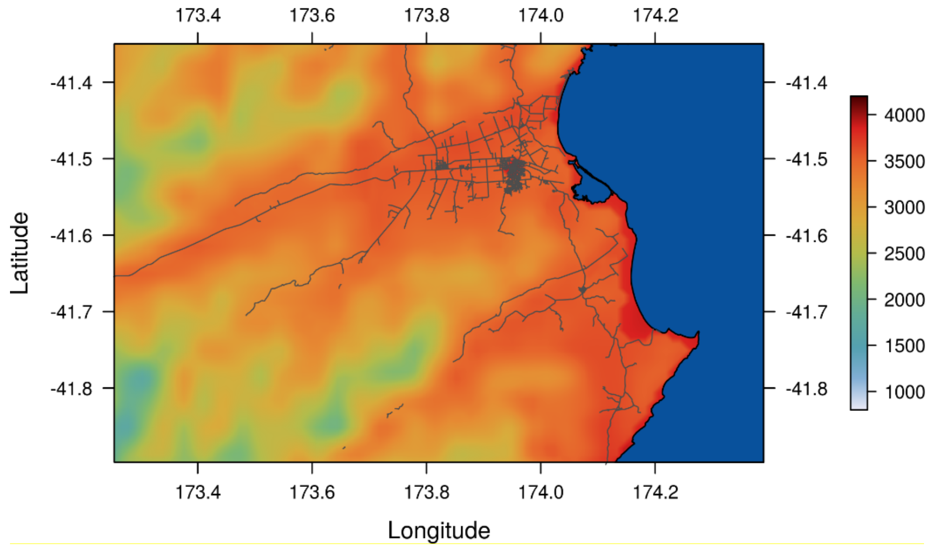
Figure 31: Example of growing degree-day (GDD) accumulation map of the Marlborough vineyard region for 29 August 2013 to 30 April 2014 derived using the Grapevine Flowering Véraison model (threshold = 0°C) based on Weather Research and Forecasting model temperatures.

Maps of three bioclimatic indices (GDD accumulation from the GFV model, the Huglin Index and the Cool Nights index) have been averaged over the six growing seasons since 2008-9 based on retrospective WRF model runs, as shown in Figure 32. They provide an indication of the spatial variation of different aspects of the thermal regime, with the GFV model focused on the relationship between air temperature and key stages in grapevine development, the Huglin Index providing a general categorization of the thermal environment and its suitability for grape production, and the Cool Nights index providing an assessment of the influence of cool nocturnal temperatures on aroma development in the grapes (Philippe et al. 2013). Not surprisingly, the spatial patterns shown by the GFV GDD accumulation and the Huglin Index (Figures 32a and b) are generally similar as they are both based on mean daily temperatures, with the Wairau and Awatere Valleys standing out as the warmer parts of the region. The main difference appears to be along the narrow coastal strip, where the marine influence appears more marked in the pattern of GFV GDD with the Huglin Index showing a more gradual increase with distance inland. The Huglin Index map suggests that most of the current area occupied by vineyards falls into either the ‘very cool’ (1200-1500) or ‘cool’ (1500-1800) categories (Figure 32b). The map of the Cool Nights index (Figure 32c) also reflects the cool climate environment of the Marlborough region in the final weeks before harvest, with most of the area falling into the ‘cold nights’ (≤ 12°C), with the coastal fringe being classified as ‘very fresh nights’ (> 12 and ≤ 14°C). These are the conditions that produce the characteristic aromas associated with Marlborough Sauvignon blanc that make it internationally popular.

The bioclimatic index maps for individual seasons are provided in Appendix B, indicating the variability between different growing seasons of the thermal environment that creates inter-annual differences in wine style and quality. As mentioned previously, the lack of strong inter-seasonal variability in mean temperatures since about 2000 is clearly evident, so that the spatial variability created by the terrain and distance from the sea appears to be significantly greater than the variation between seasons. The 2011-12 season was the coolest overall (Figures B1d and B2d), while the 2008-9 (Figures B1a and B2a) and 2012-13 (Figures B1e and B2e) seasons stand out as the warmest. In 2012-13, the Huglin Index suggests that the coastal strip was particularly warm, in contrast to other seasons when it appears to have been consistently cooler than inland areas (Figure B2).

The higher GFV GDD values that occur consistently along the coast appear to contrast with the situation in some other parts of the world, such as the Western Cape region of South Africa, where the sea breeze acts to moderate daytime temperatures (Bonnardot et al. 2002, 2005). However, the Marlborough region of New Zealand is an ideal environment for cool climate grape varieties, as it is located further south at around 41.9º S (cf. 34º S of the Western Cape) and is subject to greater nocturnal cooling inland due to the combination of the complex terrain and its situation in relation to prevailing weather systems. When averaged over the growing season, this nocturnal cooling appears to be reduced in the coastal strip under the influence of maritime effects, so that daily average temperatures are slightly higher, creating a strip of higher GDD accumulation along the coast. This effect will be investigated further in subsequent research.

a)



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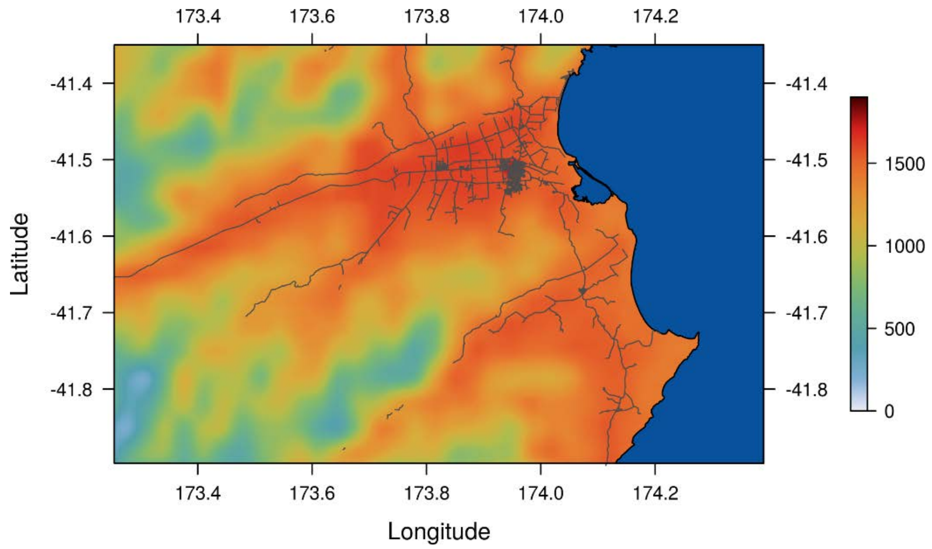

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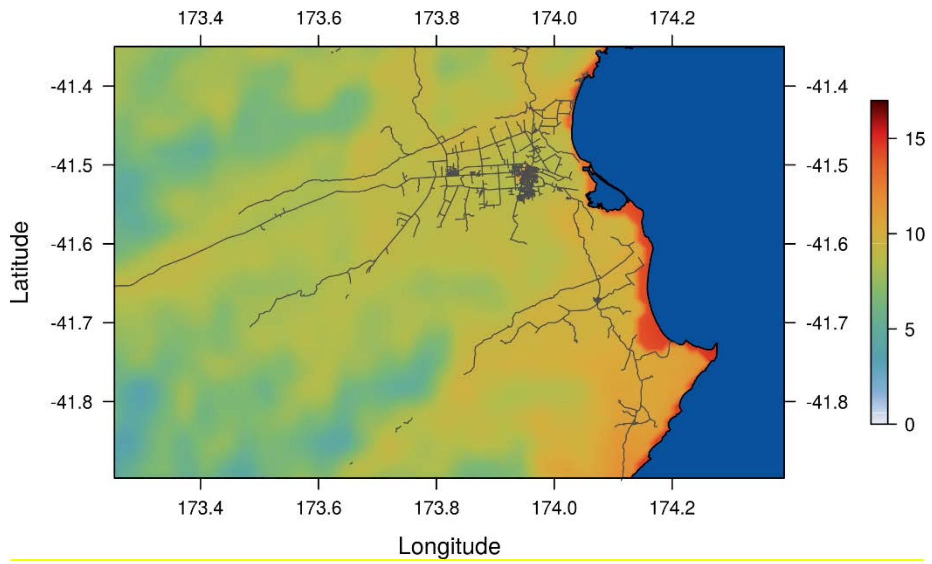


Figure 32: Maps of bioclimatic indices for the Marlborough vineyard region averaged over the six growing seasons from 2008-9 to 2013-14 based on Weather Research and Forecasting model temperatures: a) GDD accumulation from the GFV model (period = 29 August to 30 April, threshold = 0ºC); b) the Huglin index (period = 1 October to 31 March, threshold = 10ºC); and c) the Cool Nights index (March average minimum temperature).

4. Application of modelling techniques to prediction of key developmental phases of the grapevine (flowering and véraison) using the new Grapevine Flowering Véraison model

As mentioned earlier, the GFV phenological model has been integrated with the WRF meteorological model to provide the basis for a high resolution assessment of the relationship between climate and grapevine response. Simulation and/or prediction of the key phenological stages of flowering and véraison has been the initial focus of this part of the work, and has involved the analysis of WRF model output alongside field data obtained from automatic weather stations and detailed monitoring of grapevine response (Figure 33 and Table 6). The flowering stage tends to develop at each site over several days as a function of the prevailing weather conditions, and Figure 34 illustrates the typical differences that can be experienced between sites in term of both the date and duration of flowering. The date in each growing season on which 50% of the flowering has taken place is used in this study to compare grapevine development between sites and seasons. Temperatures at this time have important consequences for vine development, affecting fruit set in the current growing season and bunch number per shoot in the subsequent growing seasons (Trought 2005, Vasconcelos et al. 2009).

Figure 33: Satellite map of Marlborough, New Zealand, showing location of sites of Sauvignon blanc phenological observations. Pins: sites used for both seasons for phenology (2013-14, 2014-15). Star symbols: sites used in 2013-14 only. Square symbol: site used for 2014-15 only. Each phenological site has an Automated Weather Station (AWS) on site or close by (the greatest distance between a phenological site and AWS is 2.9 km, and the average distance is 0.6 km).

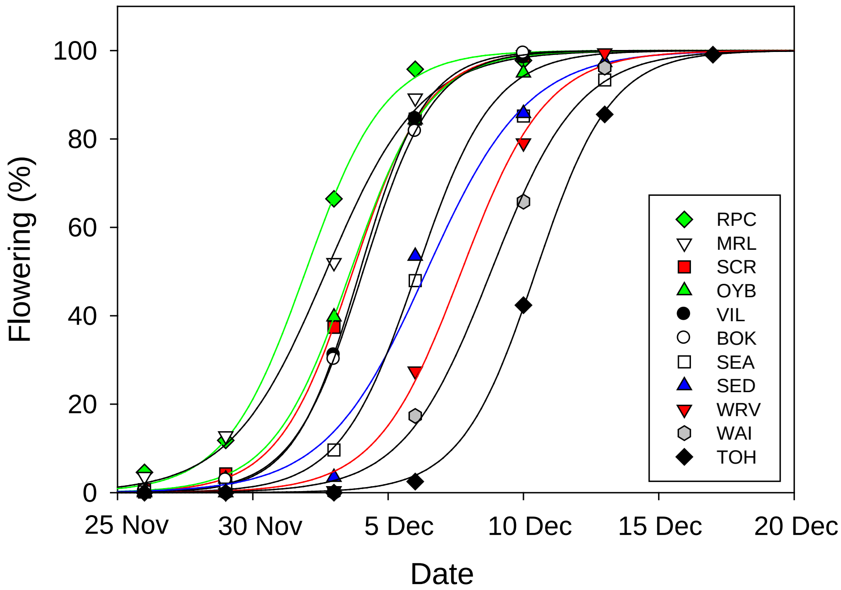


Figure 34: Sauvignon blanc flowering development for 11 sites located close to automatic weather stations in the Marlborough vineyard region in November/December 2013 based on visual observations. Sites are ordered from the earliest to reach 10% flowering to the latest. All curves were fitted to the Gompertz function, $y = 100e^{\left(-e^{(-b(x-m))}\right)}$, where the value 100 corresponds to the maximum percentage for flowering, b corresponds to the rate constant, m is the inflection point on the curve, and x is the date.

Table 6: Comparison of observations of Sauvignon blanc flowering for the 2013-14 season with simulations generated from the Grapevine Flowering Véraison (GFV) model using data obtained from Automated Weather Stations (AWS) and Weather Research and Forecasting (WRF) model output. Note the calculations for GFV started on 29 August in the Southern Hemisphere.

Site	Observed date of flowering (50%)	Simulated flowering date using AWS data	Difference between GFV simulation using AWS recorded data and observed date of flowering (days)	Simulated flowering date using WRF simulated data	Difference between GFV simulation using WRF simulated data and observed date of flowering (days)
RPC	2/12/2013	3/12/2013	1	2/12/2013	0
MRL	3/12/2013	5/12/2013	2	4/12/2013	1
BOK†	4/12/2013	5/12/2013	1	5/12/2013	1
SCR/LWV	4/12/2013	3/12/2013	-1	2/12/2013	-2
OYB	4/12/2013	4/12/2013	0	4/12/2013	0
SEA	6/12/2013	4/12/2013	-2	3/12/2013	-3
SED	6/12/2013	8/12/2013	2	8/12/2013	2
WRV	8/12/2013	8/12/2013	0	7/12/2013	-1
WAU	9/12/2013	8/12/2013	-1	5/12/2013	-4
TOH	11/12/2013	9/12/2013	-2	8/12/2013	-3

†BOK corresponds to the phenology site from the Plant and Food Research phenology network and the Plant and Food Meteorological station also known as BRA. The Villa phenology site was omitted for analysis with the Grapevine Flowering Véraison due to the absence of a suitable Automated Weather Station.

A major advantage of using output from the WRF model is that temperature data are available on a 1-km grid across the vineyard region. This temperature data set also allows the derivation of simulated flowering dates for Sauvignon blanc from the GFV model based on accumulated growing degree-days, as shown in Table 6 and Figure 35.

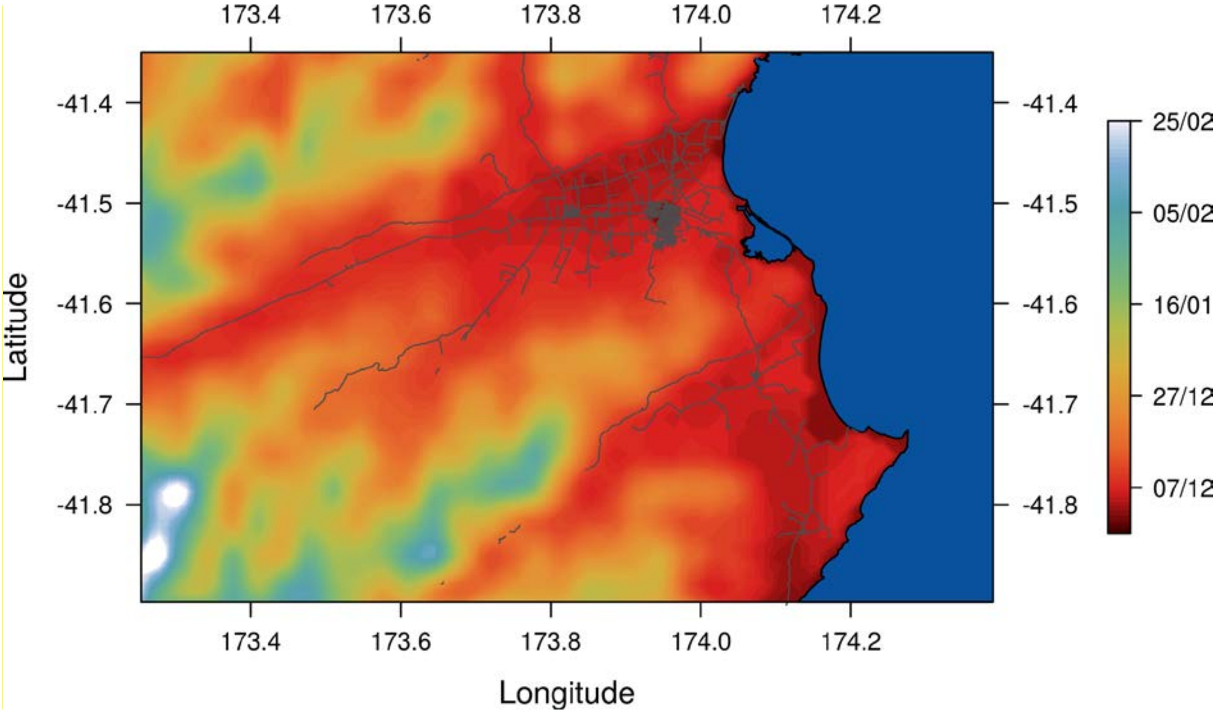
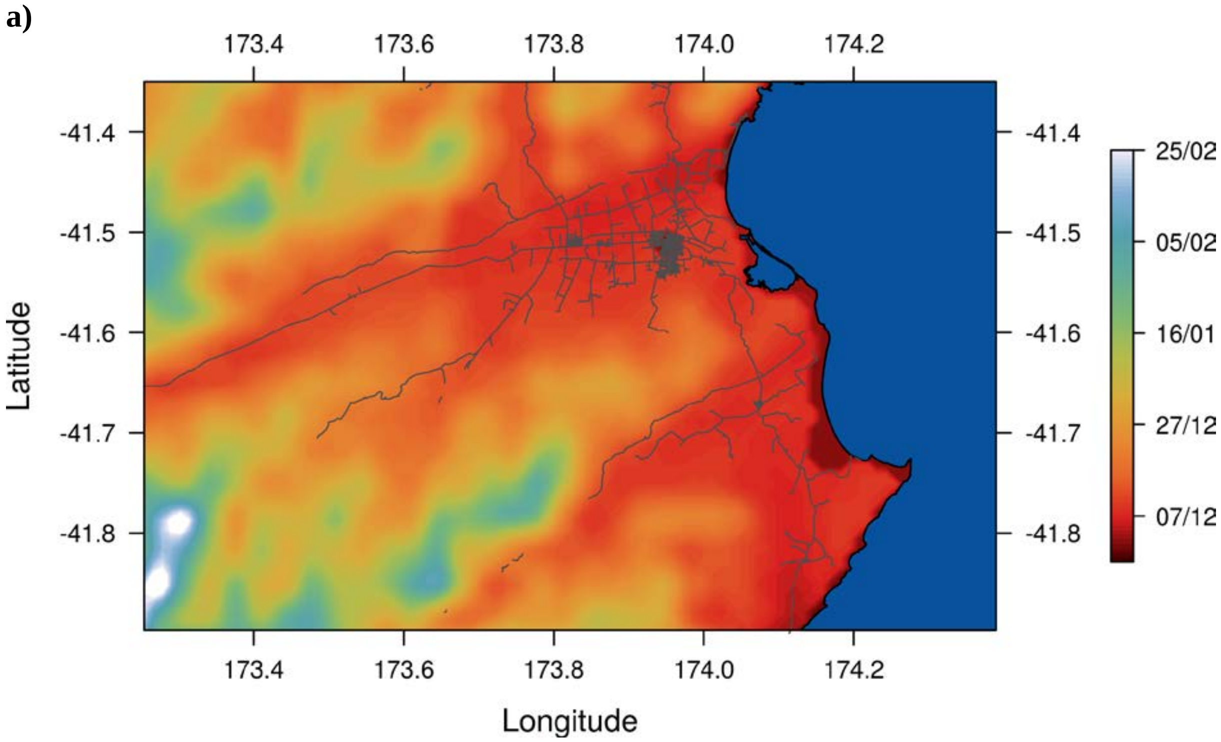


Figure 35: Map of the predicted date of flowering Sauvignon blanc based on accumulated degree-day values derived from the Grapevine Flowering Véraison model (F* = 1282) for the 2013-14 growing season across the Marlborough region, using the Weather Research and Forecasting model temperatures at 1 km spatial resolution.

As with the maps of mean temperatures and derived bioclimatic indices, the 1-km resolution temperature data from the WRF model has been used as input to the GFV phenological model to provide maps of predicted dates of Sauvignon blanc flowering (F* = 1282) and véraison (F* = 2528) during the growing seasons since 2008-9. Similar to the maps of temperature and derived bioclimatic indices, the spatial pattern of predicted dates of flowering averaged over all six seasons is dominated by the effects of terrain and distance from the sea (Figure 36), and apart from the strip along the coast, there is a general tendency for flowering in the Wairau Valley to occur slightly earlier than for the Awatere Valley (see Figure 2 for locations). The map of predicted dates of véraison averaged over the six seasons shows significantly less spatial variation, and even the coastal strip does not appear to stand out as much.

The predicted flowering dates for 2013-2014 are much earlier than for other seasons (Figure C1f in Appendix C), with those for the 2011-12 and 2010-11 growing seasons the latest (Figures C1d and c). The maps of predicted dates of véraison show a tendency for véraison to occur slightly earlier in the Wairau Valley compared with the Awatere Valley (Figure C2 and Figure 2 for locations), with more significant differences between seasons than shown for flowering. The earliest véraison over the whole region appear to have occurred in the 2008-9 and 2013-14 growing seasons (Figures C2a and f), although in 2012-13 the coastal strip is simulated to have had a very early véraison (Figure C2e). The latest véraison is simulated to have occurred in the 2011-12 growing season followed by 2010-11 (Figure C2d and c). As for the temperature and bioclimatic index maps, the WRF simulated dates of flowering and véraison will be compared with observations from vineyard records where available in future research.

a)



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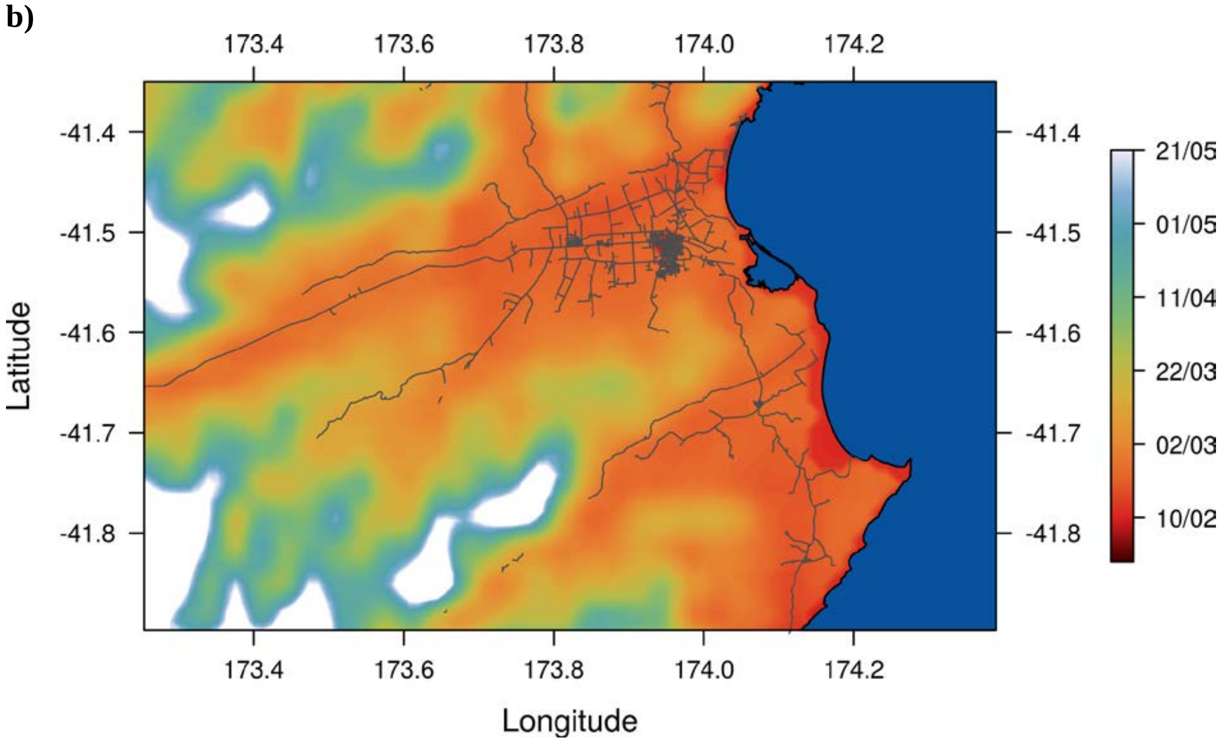


Figure 36: Maps of the predicted dates of a) flowering and b) véraison for Sauvignon blanc for the Marlborough region based on WRF temperatures at 1 km resolution averaged over the six growing seasons from 2008-9 to 2013-14, based on the GFV F* values of 1282 and 2528, respectively.

5. Development of project web site, including graphical tools for the Marlborough and Waipara regions providing hourly and longer-term information for use by the wine industry

A web site (www.wineclimate.co.nz) has been set up as one of the outcomes of this research project to deliver the results of the research to the stakeholder and scientific communities. The aim of the web site is to provide a range of different sorts of information, including:

1. New knowledge about effects of climatic variability on viticulture in New Zealand, suggesting possible strategies for adaptation to climate change.
2. Hourly maps of short-term weather forecast information (particularly temperature and wind) at vineyard scale (24 hour predictions updated every 12 hours) to assist with decision-making on a day-to-day basis.
3. Daily updated maps at 1 km resolution of accumulated GDD totals and isochrones of dates of flowering and véraison based on the WRF meteorological model and GFV phenological model during the growing season to assist with longer-term vineyard management.
4. Graphs and maps of temperature and derived bioclimatic indices allowing comparison between seasons of the spatial patterns and temporal development of the thermal climate and its potential effect on grapevine development.
5. Maps of a range of bioclimatic indices to identify the relationship between variability in local climate and different grape varieties. The GFV model can be used to investigate such relationships as model parameters have been determined for almost 100 different varieties (Parker et al. 2013).

Data in the form of various maps and graphs are mainly provided for the Marlborough region, although prototype maps for Waipara are also presented and provision of information for other regions is also planned, although this is likely to depend on available funding. Figures 38 to 41 provide some examples images from the project web pages.

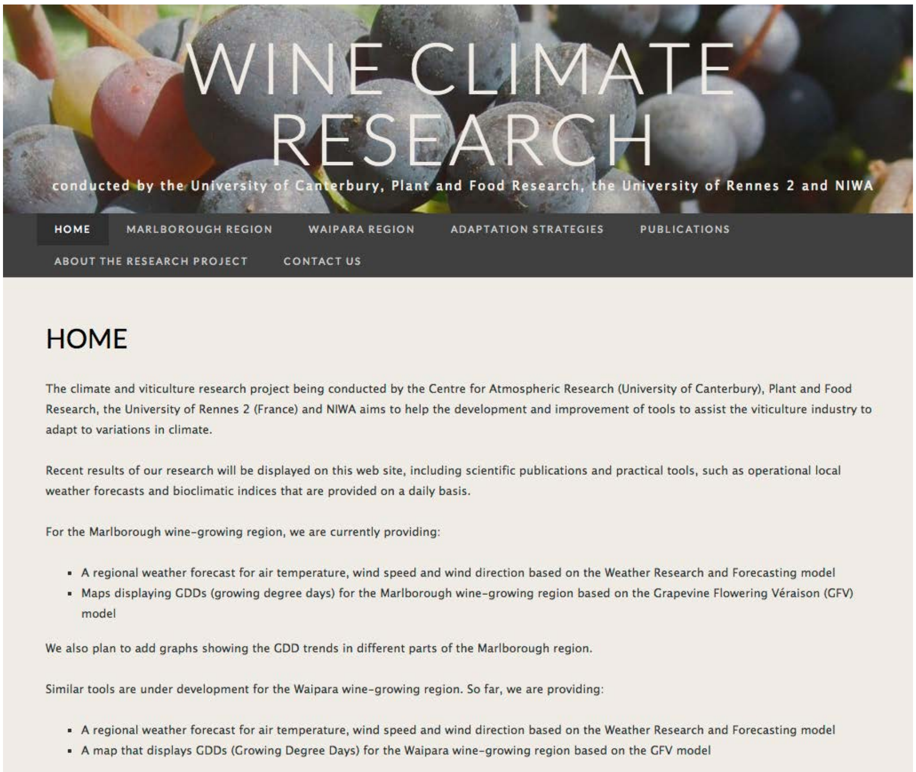


Figure 38: Home page of the Wine Climate Research web pages (www.wineclimate.co.nz).

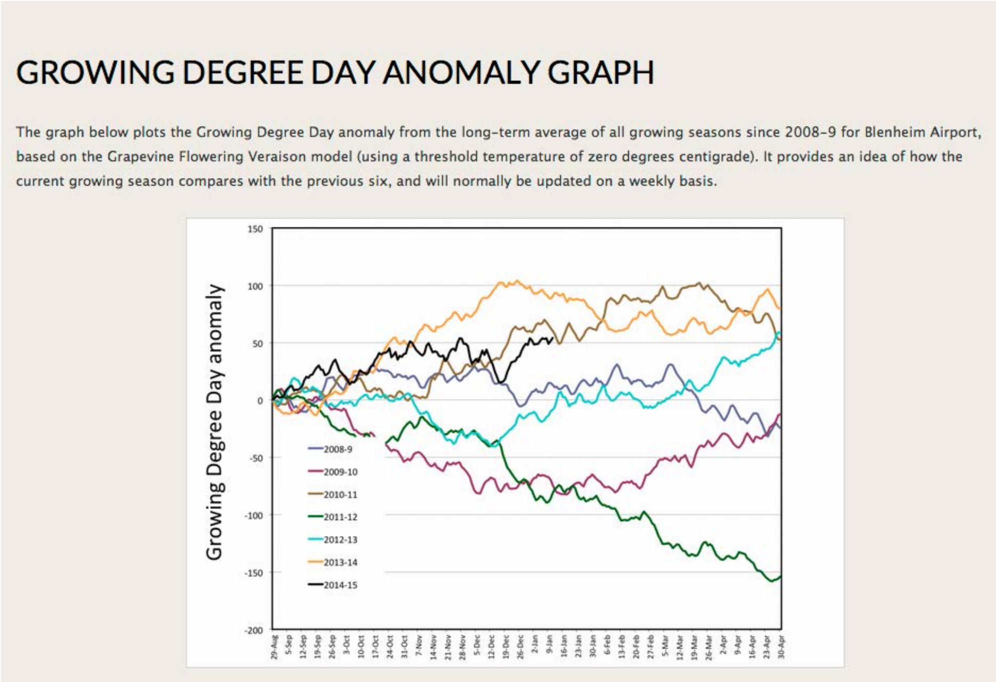


Figure 39: Growing degree-day anomaly graph for Blenheim Airport from the Wine Climate Research web pages (www.wineclimate.co.nz).

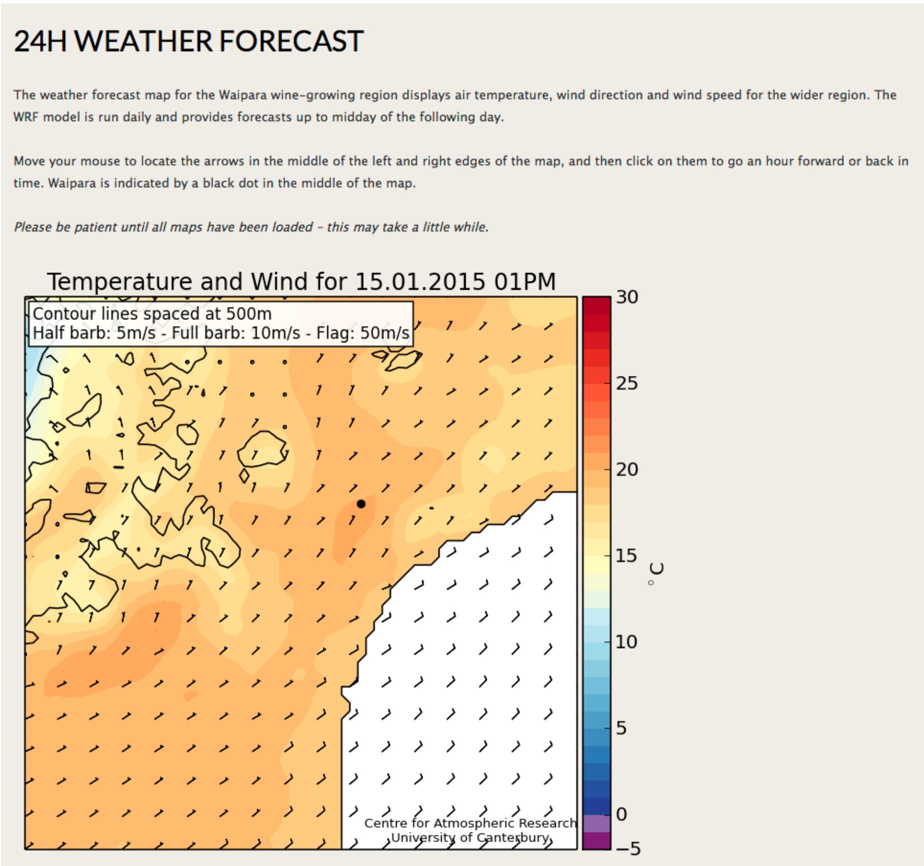
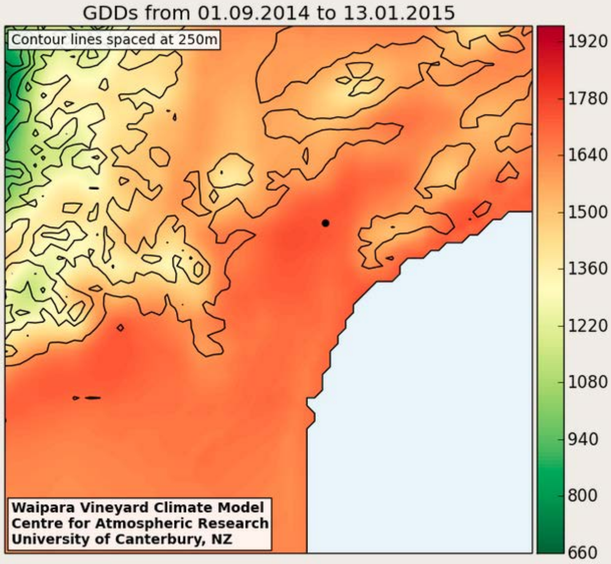


Figure 40: Example forecast map derived from WRF output for the Waipara vineyard region from the Wine Climate Research web pages (www.wineclimate.co.nz).

LATEST GROWING DEGREE DAYS

This map displays the latest accumulated Growing Degree Days (GDDs) since 1 September 2014 in the Waipara wine-growing region. GDDs were derived from the weather conditions forecast by the WRF model. The black dot indicates the Waipara growing-region.

This page will be updated regularly. So come back later to check out the latest GDD developments in the region.



Please note that the Growing Degree Days are determined using a base temperature of 0 ˚C, as in the Grapevine Flowering and Veraison model (Parker et al. 2011).

Figure 41: Example growing degree-day map derived from WRF output for the Waipara vineyard region from the Wine Climate Research web pages (www.wineclimate.co.nz).

6. Adaptation strategies for responding to weather/climate variability

6.1 INTRODUCTION

Climate change has the potential to impact on most forms of agriculture. However, the greatest economic cost may be in perennial crops, such as grapevines, where vineyards may last up to 50 years from planting, and long-term investment in infrastructure may influence the viability of the industry. It is not only the investment in vineyards that may be at risk, but also the processing wineries, which are traditionally located at or near the areas of production. Climate change also has the potential to break the traditional link between a region and variety, potentially causing a shift in wine regions (Neethling et al. 2012, Moriondo et al. 2013). Many classical winegrowing regions are associated with specific grapevine varieties and styles of wine. In many European regions, the geographic indications (appellations) only permit certain varieties to be grown. For instance, INAO (Institut National d'Origine et de la Qualité) which regulates the French Appellation d'Origine Contrôlée (AOC) system defines which grape varieties may be grown in the appellations. For example, it allows only four varieties in the Burgundy appellation (Pinot noir, Gamay, Aligoté and Chardonnay) and three in Champagne (Pinot noir, Pinot meunier and Chardonnay). While other regions may not be controlled by legislation, a strong association with region (or country) and wine variety may be recognized (e.g. New Zealand/Marlborough: Sauvignon blanc, South Australia: Shiraz). However, the rate of change in temperature does not appear to be the same in the various major wine growing regions of the world (Jones et al. 2005) and consequently how industries manage change will vary.

The key climate change factors that are predicted to impact on grapevine growth and development are:

1. A progressive increase in temperature
2. A progressive increase in mean annual atmospheric carbon dioxide concentrations
3. A change in rainfall patterns
4. Greater variability in weather patterns
5. A rise in sea level

Separating and determining the relative importance of the three environmental factors (temperature, CO_2 concentration and rainfall) that are likely to be affected by climate change is difficult. For example, an increase in carbon dioxide concentration may enhance photosynthetic rates and at the same time improve the water use efficiency (the fixation of photosynthates per unit water transpiration) (Bindi et al. 1997). This in turn may stimulate grapevine production without causing negative effects on the quality of grapes and/or wine (Bindi et al. 1995). However, the consequence of the CO_2 increase will depend on the location of the vineyard and the variety being grown (Bindi et al. 1995). The interaction with changes in temperature is still unclear, but higher yield (fruit weight to leaf area ratio) may affect phenology (see Section 6.4). Likewise, the consequence of climate change for rainfall patterns is still being debated. However, a decrease in seasonal rainfall may be accommodated by the selection of rootstocks with greater drought tolerance, such as 1103 Paulsen or 110 Richter (Serra et al. 2014) and/or greater regional water storage of winter river flows.

While grapevine phenology at any particular location may be influenced by environmental factors such as soil type (in particular soil water holding capacity and/or texture) (Tesic et al. 2001, Trought and Bramley 2011), climate warming is likely to have a similar effect across different soil types and adjusting vineyard management to accommodate the consequences of climate change will be difficult. The strategies discussed here will predominantly (but not exclusively) focus on using canopy management to respond to an increase in temperature in Marlborough, which represents about 75% of the vineyard area of the New Zealand industry.

6.2 INCREASING TEMPERATURE

The major viticultural regions of the world lie generally between latitudes 35° and 50°, within annual isotherms of 10 to 20°C (Jackson 2008). While it is not possible to define the ideal climate for fine wines, the best expression of a grapevine variety occurs when full ripeness is reached at the end of the growing season (van Leeuwen and Seguin 2006). Three climatic criteria are paramount for sustainable grape production:

- An optimum heat requirement during the season to ripen grapes to a composition suitable to enable the winemaker to achieve the desired wine style.
- Minimal frost risk during the growing season.
- A distribution of rain that allows appropriate soil moisture during the growing season, but low risk during ripening when rain may induce fungal diseases. Rainfall for growth may be supplemented by irrigation, as is generally the case in New Zealand.

As temperatures increase, vine phenology may be advanced, with the result that fruit will ripen earlier and under warmer conditions (Schultz 2000, Jones et al. 2005, Jones 2006, Trought et al. 2014). If the environment is too warm, the development of flavour may be decoupled from changes in sugar and acidity (Duchêne et al. 2014) and secondary metabolites (Sadras and Moran 2012) with an adverse effect on the traditional wine flavour and aroma profiles and a negative effect on wine quality (Jones et al. 2005). In a recent survey of 52 Marlborough winegrowers and viticulturists (with average experience of 11.3 years), participants were asked to rate the characteristics of the juices used to make a "typical Marlborough Sauvignon blanc". The optimum soluble solids, titratable acidity (tartaric acid equivalent) and pH values were 22.5 ^{o}Brix, 9.0 g/L and pH 3.2 respectively, with a relative weighting of 49, 28 and 23% (Trought and Bramley 2011). Marlborough generally experiences a prolonged, cool ripening, which enables fruit to retain a characteristic acidity, while at the same time developing a balance in the key secondary metabolites (e.g. methoxypyrazines and thiols). Warmer ripening could result in lower acidity and reduced Marlborough "typicality".

Differences between wine grape cultivars have been characterized by classifying varieties according to temperature grouping (Winkler 1948, Huglin 1978, Jackson and Cherry 1988, Gladstones 1992, Jones et al. 2005, Gladstones 2011). For example, Jackson and Cherry (1988) developed a Latitude Temperature Index (LTI) with the aim of associating grape varieties to specific climate conditions (see Table 7). The relative performance of the various variety classification systems is beyond the objectives of this report. However, these systems of temperature grouping are largely based on historic and traditional experience. For example, temperatures are defined by the variety traditionally grown in a particular area (which in turn may be controlled by legislation), rather than the reverse. So Gewürztraminer may be defined as a variety grown in extra cool climates and Sauvignon blanc in warmer climates (see Table 4; Jackson and Cherry 1988). However, in the newer wine growing regions (e.g. Marlborough), both varieties are grown successfully in adjacent vineyards, suggesting that some of the differentiation of the varieties into separate climate groups may be largely a function of where the varieties are traditionally grown, rather than related to a temperature dependent variable.

The alternative, but not mutually exclusive method of classifying varieties is to determine the timing of key phenological stages of development and how this relates to accumulated temperatures (Huglin 1978, Parker et al. 2013, Duchêne et al. 2014). This approach enables phenological development of varieties in non-traditional grape growing regions (i.e. Riesling in Bordeaux or Cabernet Sauvignon in Marlborough) to be determined. However, this approach does not take into account differences in fruit composition for alternative wine styles (e.g. the soluble solids concentration for commercial Sauvignon blanc is generally lower than Pinot noir, and that for Chardonnay/Pinot noir for sparkling wine will be lower than that required for table wine).

Table 7: Grape varieties grouped by Latitude Temperature Index (LTI)[1] according to ripening ability in different climates (Jackson and Cherry 1988).

Group and Latitude Temperature Index	Varieties
Group A: LTI < 190	
1. very cool	Gewürztraminer, Reichensteiner, Müller Thurgau
2. cool	Pinot gris, Pinot blanc, Pinot noir, Pinot meunier, Chardonnay (all these varieties may be grown for sparkling wine base). Auxerrois, Aligoté, Sylvaner, Chasselas
Group B: cool-warm LTI 190-270	Pinot noir, Riesling, Chardonnay (Table wines)
Group C: warm LTI 270-380	Sauvignon blanc, Sémillon, Cabernet Sauvignon, Merlot, Malbec
Group D: warm-hot LTI >380	Carignane, Grenache, Thompson seedless, Zinfandel

[1]LTI was developed at Lincoln University by David Jackson and Neil Cherry. LTI = mean temperature of the warmest month x (60 – latitude).

Marlborough autumns are typically cool and mostly frost free. This provides a drawn out ripening period enabling fruit to ripen and flavours to develop. It is suggested that relatively high acidity is one of the key characteristics in producing the distinctive style of Sauvignon blanc that New Zealand and, in particular, Marlborough has become famous for. The metabolism of malic acid (one of two predominant fruit acids) is greater under higher temperatures (Ruffner 1982, Reynolds et al. 1986). Higher temperatures during the ripening phase may decrease fruit acidity at a given concentration of soluble solids, and as a result changing the character of Marlborough Sauvignon blanc.

Using daily Marlborough temperature data from 1987 to 2014, and the Grapevine Flowering Véraison model (Parker et al. 2011, Parker 2012, Parker et al. 2013) the dates of flowering, véraison (8.0 °Brix) and maturity (200 g/L sugar) of Sauvignon blanc in Marlborough, New Zealand are predicted to be on average 7 December, 17 February and 22 March, respectively (Trought et al. 2014) (Figure 42). Assuming an increase in mean daily temperature of 0.5°C, these dates would be advanced to 4 December, 14 February and 17 March, while a 2.0°C increase would advance the dates to 22 November, 26 January and 24 February, respectively. While a 0.5°C increase in temperature results in a small advance in phenology, most seasons would still fall within the current seasonal variation experienced in Marlborough. In contrast, a 2.0°C increase would result in phenology well in advance of that currently experienced in Marlborough, apart from exceptionally warm seasons. For example, maturity date is predicted to be between 17 February and 1 March compared to current dates of 13 March to 31 March (10 to 90% of seasons).

By applying the two warming scenarios mentioned above it could be expected that the time of the ripening period (véraison to harvest) would be advanced and therefore the temperatures experienced by vines during this period would differ (Figure 43). Currently in Marlborough, the mean daily temperature during ripening is 16.5°C. If mean daily temperatures increased by 0.5 and 2.0°C the mean ripening temperatures would increase by 0.8 and 3.9°C, respectively. The higher ripening temperatures reflect a combination of the earlier ripening dates and the higher mean daily temperatures at that time of the year. The data suggest that Sauvignon blanc production in a Marlborough climate that had warmed by 0.5°C would be similar to that experienced in Hawke's Bay today. Alternatively, changes in vine management to delay the onset of véraison by five days could accommodate a 0.5°C increase in temperature, with the result that ripening temperatures (and potentially flavour and aroma profiles) would be similar to those of today. However, warming by 2.0ºC would require relocation of Sauvignon blanc vineyards to higher latitudes and/or altitudes to maintain a wine profile similar to today. It seems likely that these vineyards would be replaced by other varieties, currently grown in warmer climates. Of course, by the time we experience a 2.0ºC increase in temperature, tastes may also have changed.

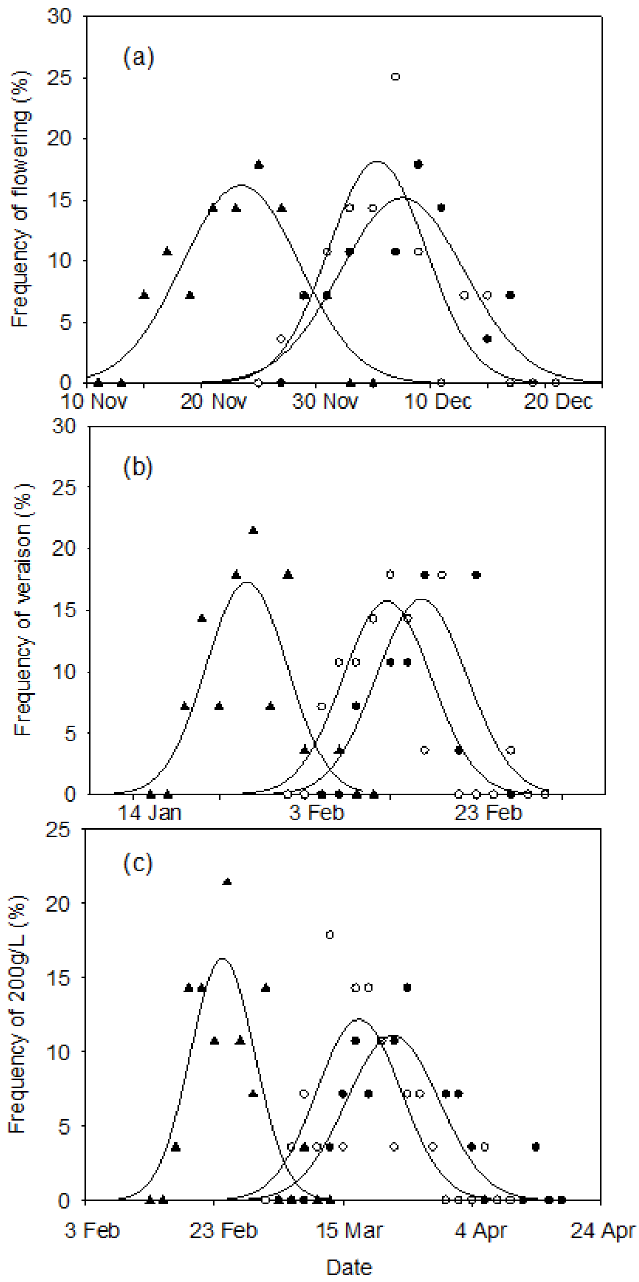


Figure 42: Frequency of seasons (1987 to 2014) in which Sauvignon blanc is predicted to reach (a) flowering, (b) véraison and (c) maturity by a particular date in Marlborough using the Grapevine Flowering Véraison Model and daily temperature for current temperatures (●), current temperatures +0.5ºC (○) and current temperatures +2.0ºC (▲) (adapted from Trought et al. 2014). Gaussian 3-parameter curves were fitted using SigmaPlot 12.5.

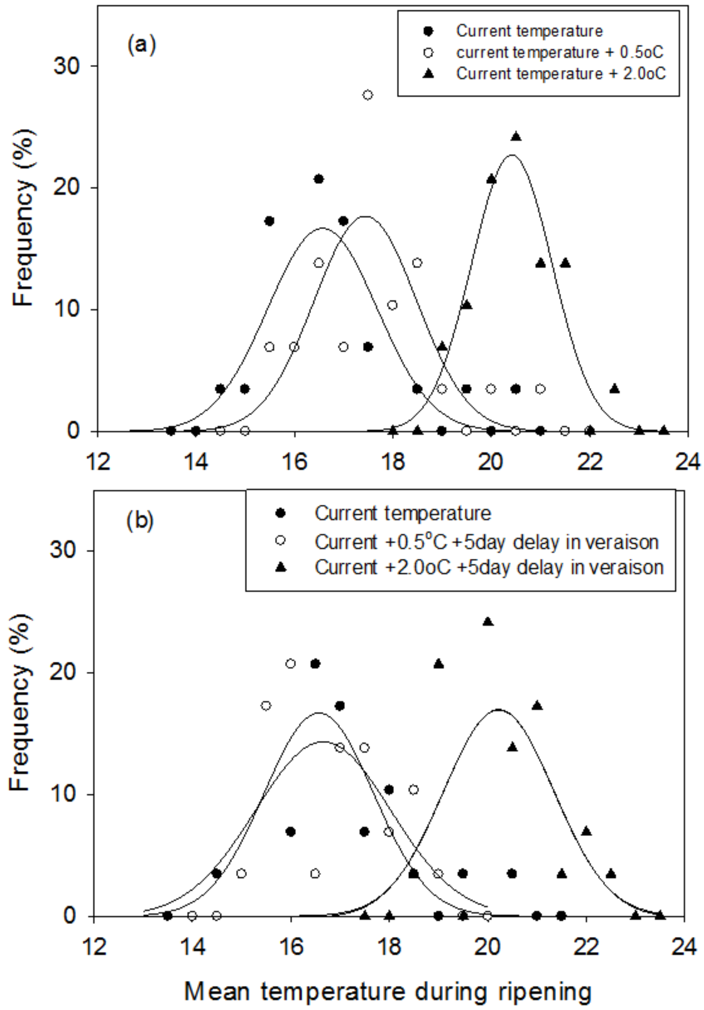


Figure 43: Predicted mean daily temperatures during ripening of Sauvignon blanc (from 8 to 20°Brix) using (a) current Marlborough (1987 to 2014) temperatures (●), current temperatures +0.5°C (○) and current temperatures +2.0°C (▲) and (b) current temperature (●), current temperatures +0.5°C + 5 day delay in veraison (○) and current temperatures +2.0°C + 5 day delay in véraison (▲) (adapted from Trought et al. 2014). Gaussian 3-parameter curves were fitted using SigmaPlot 12.5.

6.3 FROSTS AND FROST VULNERABILITY

Grapevines become vulnerable to frost when growth starts early in the spring. A damaging frost shortly after budburst can result in a severe reduction in grapevine yield in the current season and additional pruning costs in the following season caused by difficulties in selecting appropriate canes (Trought et al. 1999). Any advance in the date of the last frost resulting from climate change is likely to be associated with an earlier budburst time, with the result that the frost risk is unlikely to change a great deal (Trought 2008). This scenario assumes that daily maximum and minimum will be influenced in a similar way. Should maximum daily temperatures increase to a relatively greater degree than minimum night-time temperatures, then budburst may be advanced more than the date of the last frost, so that the vulnerability of vineyards to spring frost damage may in fact be increased. Likewise, a change in the climate patterns in early spring, particularly if there is an increase in high pressure patterns (and thus clear skies at night) may increasing the frost risk to vines (as discussed earlier in Section 2).

6.4 POTENTIAL ADAPTION STRATEGIES TO COPE WITH CLIMATE CHANGE IN NEW ZEALAND VINEYARDS

The alternative management strategies that might be considered to cope with climate change can be divided into two key areas (Figure 44). First is the long-term adaptation of the vineyard, which generally involves either developing vineyards in new regions or replanting existing vineyards. Alternatively, short-term vine management may be adjusted to accommodate a seasonal change in temperature. In general, short-term management changes will have a relatively small effect on vine development, when compared to long-term adaptation practices, but decisions can be made on a seasonal basis. For example, canopy area may be reduced by trimming shoots lower in a warmer than average season.

6.4.1 Long-term management changes

Long-term management strategies largely focus on identifying new areas to plant existing grapevine varieties (generally at higher latitude or altitude), or changing the grapevine variety to match the existing area (Moriondo et al. 2013, Kenny and Harrison 1992). This may in some circumstances be achieved by identifying cooler vineyard areas within a geographic region (Anderson et al. 2012). However, changing to new varieties in traditional vineyard appellations may prove to be difficult, in some cases requiring changes in legislation. In contrast, in wine producing regions where legislation does not control the varieties that may be grown, a shift in varieties may be easier (Anderson et al. 2012). For example, there is no control over which varieties can be grown in Marlborough, and to some extent the suitability of varieties has been determined by trial and error over the past 30 years.

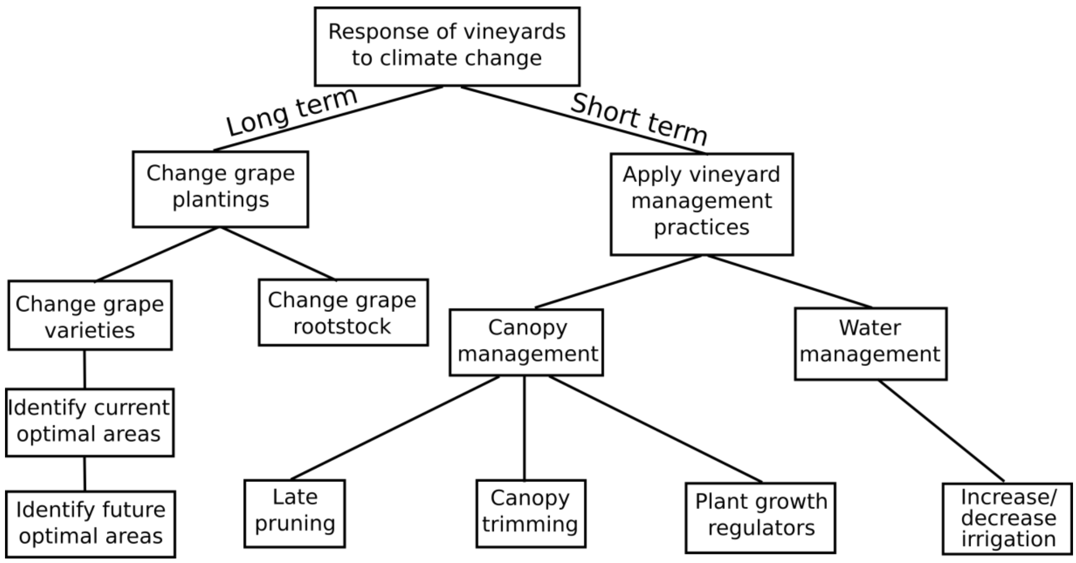


Figure 44: Potential vineyard adaptation strategies used to cope with climate change at the regional scale (long-term) or local/plot scale (short-term).

Changing grapevine varieties and/or rootstock

Unlike the traditional grapevine variety grouping models described above, the Grapevine Flowering Véraison (GFV) model describes the accumulated degree-days required by approximately 100 varieties to achieve specific stages of development (Parker et al. 2013). Table 4 shows the F^* values for flowering and véraison for some key varieties. This enables the selection of appropriate varieties to be considered, taking into account a long-term change in temperature. The date of véraison is central to the suitability of varieties to a particular environment and while the date of véraison is influenced by other factors such as extreme reductions in the leaf area to fruit weight ratio (Parker et al. 2014b), it is largely controlled by temperature. However, the rate of soluble solids accumulation from véraison onwards appears to reflect the leaf area to fruit weight ratio and be independent of variety (Sadras and Petrie 2011a, 2011b, Parker 2012).

While rootstock selection can influence berry quality parameters (Kodur et al. 2013) and reproductive performance (Kidman et al. 2014), many of these responses appear to be secondary effects resulting from differences in nutrients (in particular potassium) and water stress (reflecting differences in the rooting patterns of the different rootstocks; Swanepoel and Southey 1989). However, it would appear likely that under conditions of increased temperatures and an increase in the likelihood of water stress, a progressive shift will occur to more drought tolerant *Vitis berlandieri x Vitis rupestris* rootstocks (e.g. 1103 Paulsen or 110 Richter) and away from *Vitis riparia* based rootstocks (e.g. Schwartzman, 101-14 Mt and 3309 Couderc; Serra et al. 2014) that are currently frequently used in New Zealand vineyards and that exhibit a more superficial rooting pattern.

Research is currently attempting to produce cultivars and rootstocks that are better able to handle environmental changes associated with climate change. For example, new drought resistant rootstocks are being developed (rootstocks currently in use were generally developed in the 19th Century to combat Phylloxera in Europe). However, recently CSIRO Australia have been breeding rootstocks with greater drought tolerance that can be irrigated with saline water (Walker and Clingeleffer 2009, Walker et al. 2014). At the same time, grapevine breeding efforts have resulted in a range of new winegrape varieties (Reisch et al. 2014) with greater disease resistance and/or flavour and aroma profiles. These breeding efforts have used traditional breeding techniques, the identification of trait analysis using Next Generation Sequencing (see http://www.vitisgen.org/extension.html) and/or genetically modified plants (Webb et al. 2011). Only time will tell the extent to which industry will adopt these new varieties.

6.4.2 Short-term management options

An alternative approach to using long-term strategies to adapt to higher temperatures is to adopt management practices that may delay the development cycle within a season, in particular the date at which the ripening process starts (véraison). While these practices can be adopted or not, depending on the vine development of any particular season, the effect on phenology is likely to be small, when compared to the long-term strategies.

Manipulating development post-flowering

Alternative methods of delaying the date of véraison include late spur-pruning, to delay vine phenology, or increasing the time from flowering to véraison either by: 1) trimming shoots or removing leaves to reduce the leaf area to fruit weight ratio; 2) slowing photosynthetic rates post-flowering by the application of anti-transpirants; or 3) the use of plant growth regulators.

Reducing net vine photosynthesis of grapevines can significantly affect fruit development. Reducing photosynthesis pre-flowering (either by leaf removal, trimming shoots or the application of anti-transpirants that impede gas exchange through the leaf stomata (Anderson and Kreith 1978) can reduce fruit set and yield, advancing véraison and ripening (Caspari et al. 1998, Palliotti et al. 2011). Similar treatments post-fruit set can delay the onset of véraison. For example, trimming the canopy of vines shortly after fruit set, to reduce canopy area to less than 0.75 m^2/kg fruit can increase the time from flowering to véraison date by approximately 5 days (Parker et al. 2014b). Likewise, a 30% reduction in leaf area pre- or post-véraison has been seen to delay harvest date of Sangiovese grapevines by approximately seven days (Poni et al. 2013). Similarly, trimming Grenache vines to reduce leaf area by between 30 and 60% delayed véraison date by approximately 17 days and harvest date by approximately 14 days, depending on the season (Martinez de Toda et al. 2014). Interestingly, the delayed harvest caused by the trimming treatment resulted in higher anthocyanin concentrations at the same soluble solids at harvest in both Grenache and Tempranillo (Martinez de Toda et al. 2014).

Spur-pruning vines late in the winter (at about the time of bud-break) can delay the onset of bud-break by eight to 11 days (Dami et al. 1997, Martin and Dunn 2000, Friend 2005, Friend and Trought 2007) when compared to traditional mid-winter pruning. This can in turn result in a delay in flowering and véraison dates of up to four or five days (Martin and Dunn 2000, Friend 2005). While this may work, it means that vines would need to be pruned in a very limited time frame which may limit its application to small producers and not be feasible for large scale operations.

More recently, pre-véraison applications of 1-naphthaleneacetic acid (NAA) have been shown to delay véraison by 12 to 40 days, with similar effects on the time taken for fruit to reach 20 °Brix (Böettcher et al. 2011, Ziliotto et al. 2012).

Manipulating sugar and acidity changes in developing fruit

The rate of soluble solids accumulation and, as a consequence, the date at which a target soluble solids is achieved is strongly affected by the leaf area to fruit weight ratio (Poni et al. 2013, Parker et al. 2014b, Parker et al. 2014c). However, changes in the leaf area to fruit weight ratio has little effect on titratable acidity (Parker et al. 2014a, Parker et al. 2015). As a consequence, alternative methods to maintain fruit acidity may be needed, particularly as the degradation of malic acid (one of two predominant fruit acids) is greater under higher temperatures. Shading bunches either by changing vine management to increase leaf cover may result in significantly lower fruit temperatures, and an increase in fruit malic acid concentration and titratable acidity at harvest (Reynolds et al. 1986). Alternatively, the use of shade netting may provide an alternative method, although further research is needed to evaluate this strategy and its value in managing temperature changes resulting from climate change.

The vine yield may in turn be moderated by the training system used (Figure 45). Training systems that produce higher yields can result in lower soluble solids at a particular date (Trought et al. 2009). However, as mentioned earlier, grapevine phenology may be influenced by other factors, and in this case the yield:soluble solids relationship may be influenced by soil water holding capacity. Vines that experience a degree of water stress ripen more slowly and at higher yields have lower soluble solids when compared to less stressed vines on higher water holding capacity soils. While the timing of ripening differs between seasons, the effect of grapevine yield is seen to remain consistent (data not shown).

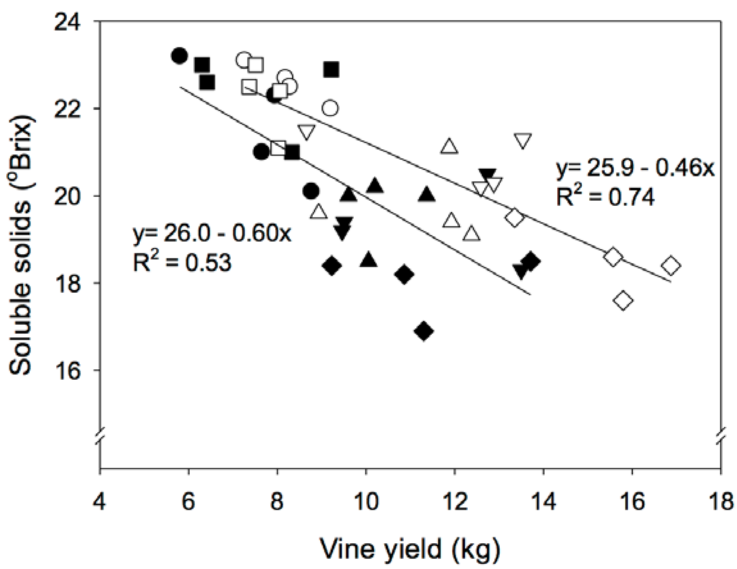


Figure 45: Influence of training system and Sauvignon blanc vine yield on soluble solids at harvest in 2008 (Trought et al. 2009). Vines were trained for four consecutive growing seasons (2004 to 2008) using five alternative training systems: ●2-cane vertical shoot positioned, ▼Scott-Henry trained, ▲4-cane vertical shoot positioned, ■ Spur pruned, ♦ Mid-height Sylvoz. Within the trial area there were soils with higher (open symbols) lower (closed symbols) water holding capacity. A full description of the training systems can be found elsewhere (Smart and Robinson 1991).

6.4.3 Summary

In general, New Zealand would appear to be in a good position to cope with a small, progressive increase in temperature resulting from climate change. An increase in temperature of less than 1^{o}C can probably be accommodated by changes in current seasonal vineyard practice (e.g. by decreasing the leaf area to fruit weight ratio and/or delaying the date of véraison). This might need to be accompanied by reducing the degree of fruit exposure to maintain fruit acidity (in particular Sauvignon blanc) and preventing excess heating which may reduce colour development and/or the concentrations of other secondary metabolites. However, these modified management practices are unlikely to cope with a greater increase in temperature. Under these circumstances, vineyards will need to be relocated to cooler regions, or alternate varieties may need to be considered.

7. Summary and conclusions

The main aim of this research was to develop new knowledge and a set of analytical tools and datasets to help wine producers adapt to local spatial and temporal variations in climate in New Zealand's vineyard regions, and thereby to help ensure the future sustainability of the industry. The research involved several inter-related phases, starting with an assessment of existing climate data for the main vineyard regions of the country, but with a particular focus on the Marlborough region as it is New Zealand's premier wine producing region. As air temperature is considered to be the most important environmental factor affecting variations in grapevine response, it was the variable selected for the most detailed analysis in this study.

An analysis of IPCC projections of future climate and recent inter-decadal trends in observed air temperature established the context for the rest of the research. Projections of future air temperatures for the Marlborough region based on IPCC SRES scenarios suggest that temperature increases through to 2050 are likely to remain within the typical inter-annual range, while by the end of the century they could lie beyond this range (Philippe et al. 2013). However, it is evident from analysis of observed temperature trends in New Zealand vineyard regions since 1940 that there are significant regional differences, with Marlborough showing virtually no warming trend in mean annual temperatures, but instead a trend of increasing daily temperature range and frost occurrence over recent decades. Further investigation identified that this trend occurred at a number of sites in or close to vineyard regions, and appears to be related to changes in weather patterns affecting the New Zealand region resulting from hemispheric scale changes in atmospheric circulation. For example, an increase in the frequency of anticyclones over the past few decades is associated with an increase in the Southern Annular Mode (representing a major shift in Southern Hemisphere atmospheric circulation), as well as an increase in the occurrence of southerly airflow over the region (Sturman and Quénol 2013).

The analysis of recent temperature trends in New Zealand vineyard regions identified that it is overly simplistic to just downscale global scale model predictions of air temperature to the regional and local scale without properly considering the effect of the smaller scale processes that global models are unable to represent (because of their coarse resolution). The weather and climate of New Zealand experiences significant local and regional variations as a result of the very complex terrain (Sturman and Tapper 2006). The methodology selected for this research was therefore based on the application of meteorological models that have been specifically designed to investigate local and regional weather and climate (at horizontal resolutions of a few hundred metres or less), and their integration with a new phenological model, thereby allowing grapevine response to be related to fine-scale variations in climate in the regions of complex terrain where vineyards have been developed.

The Weather Research and Forecasting (WRF) model was used to simulate meteorological variables such as air temperature at 1 km horizontal resolution across both the Marlborough and Waipara regions. The model simulations have been validated using meteorological data from an enhanced network of nearly 40 weather stations in the Marlborough region, and the model found to have a slight cold bias at most sites across the region. In spite of this cold bias, the model was found to perform well. WRF model output was used to derive maps of growing degree-days and flowering dates for Sauvignon blanc for the grapevine growing season that compared well with values calculated from automatic weather stations and obtained from field observations within individual vineyards. The integration of the high-resolution weather/climate model with the new phenological model provides the basis for improving crop models for predicting harvest quantity and quality of a range of grape varieties, as well as for developing appropriate adaptation strategies for responding to climate change.

Retrospective model runs were also conducted using WRF for the growing seasons since 2008-9, allowing a high spatial resolution inter-seasonal comparison of the growing conditions that influence grapevine response and harvest quality. The spatial patterns of temperature and derived variables over Marlborough show the influence of the complex terrain and distance from sea on the thermal regime of the vineyard region. The maps also provided a perspective on inter-seasonal variability of climate across the region, although such variability has been relatively subdued over the last decade in line with national temperature variability.

A web site has been developed to communicate the results of this research to the wider stakeholder community through the provision of data, maps and graphs, as well as a summary of possible strategies for wine producers to respond to climate variability and a list of relevant publications produced by the research group. The direct transfer of research results to the stakeholder community (i.e. the winegrowers) via an operational web site appears to be an innovation that has not yet been observed in other parts of the world. Twice-daily model runs have been used to provide 24-hour forecasts of hourly wind and air temperature for both the Marlborough and Waipara vineyard regions during the 2013-14 and 2014-15 growing seasons, while accumulated growing degree-days have been calculated daily and mapped over the two regions to provide an indication of the spatial variation in development of the season. Comparison with previous growing seasons has also been provided.

The new knowledge and modelling and analytical tools developed by this research project will be developed further and applied to other vineyard regions of New Zealand, as well as in other parts of the world through the links that the research group has established with the international community. In particular, application of the high-resolution weather and climate model and its integration with traditional and new phenological models will continue to be refined and improved to allow for a range of grape varieties and the specific conditions found in different vineyard regions. During this process, the stakeholder community will be consulted to help establish priorities for future work and to help develop appropriate online tools for delivering new knowledge and information to wine producers. The same techniques can also be applied to a range of different agricultural crops and discussions have been initiated with agencies interested in such applications.

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Appendix A: Temperature maps of the growing seasons from 2008-9 to 2013-14

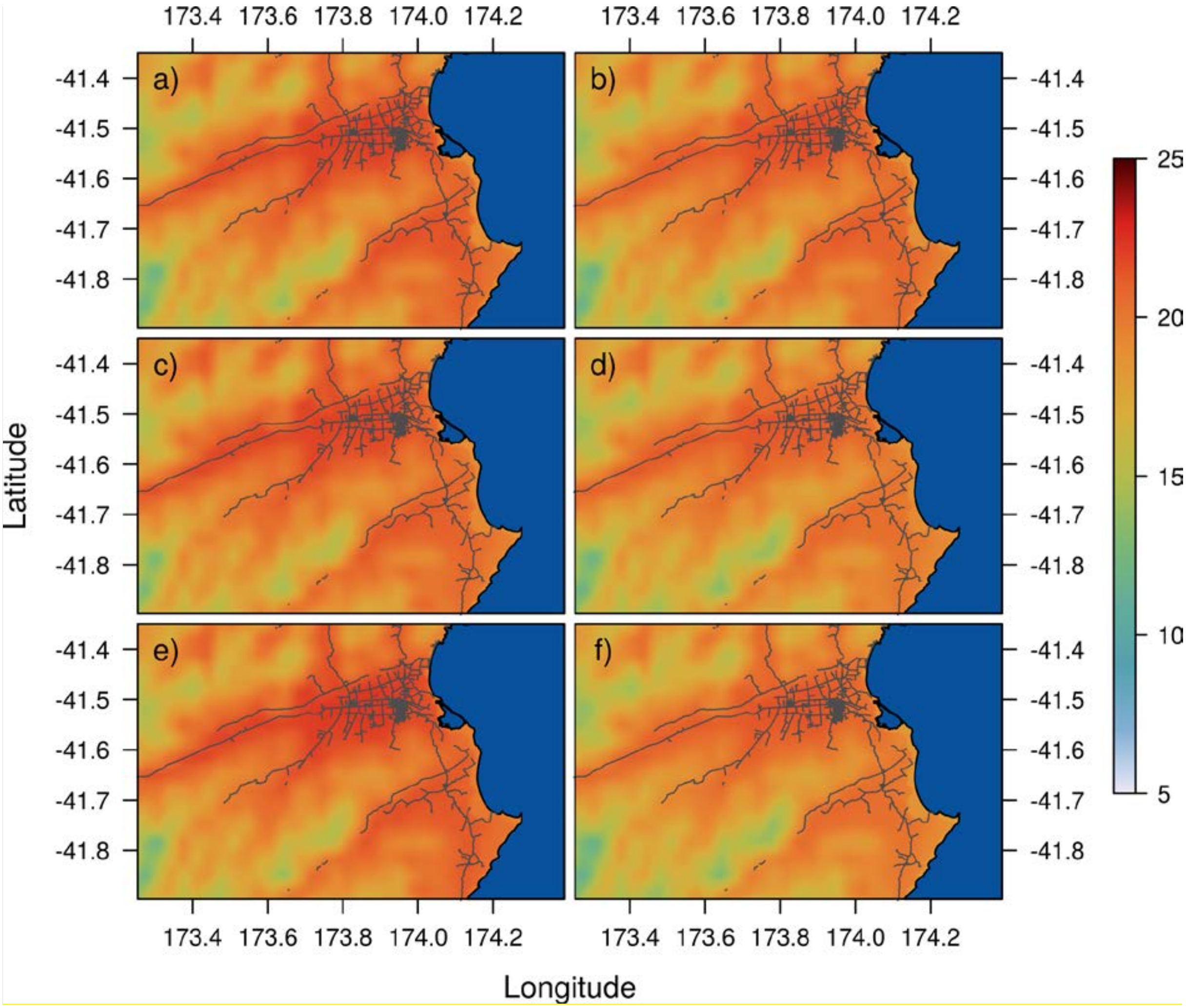

Figure A1: Maps of daily average maximum temperature (ºC) over the growing season (1 October to 30 April) for the Marlborough region using WRF output for a) 2008-9, b) 2009-10, c) 2010-2011, d) 2011-2012, e) 2012-2013, f) 2013-14.

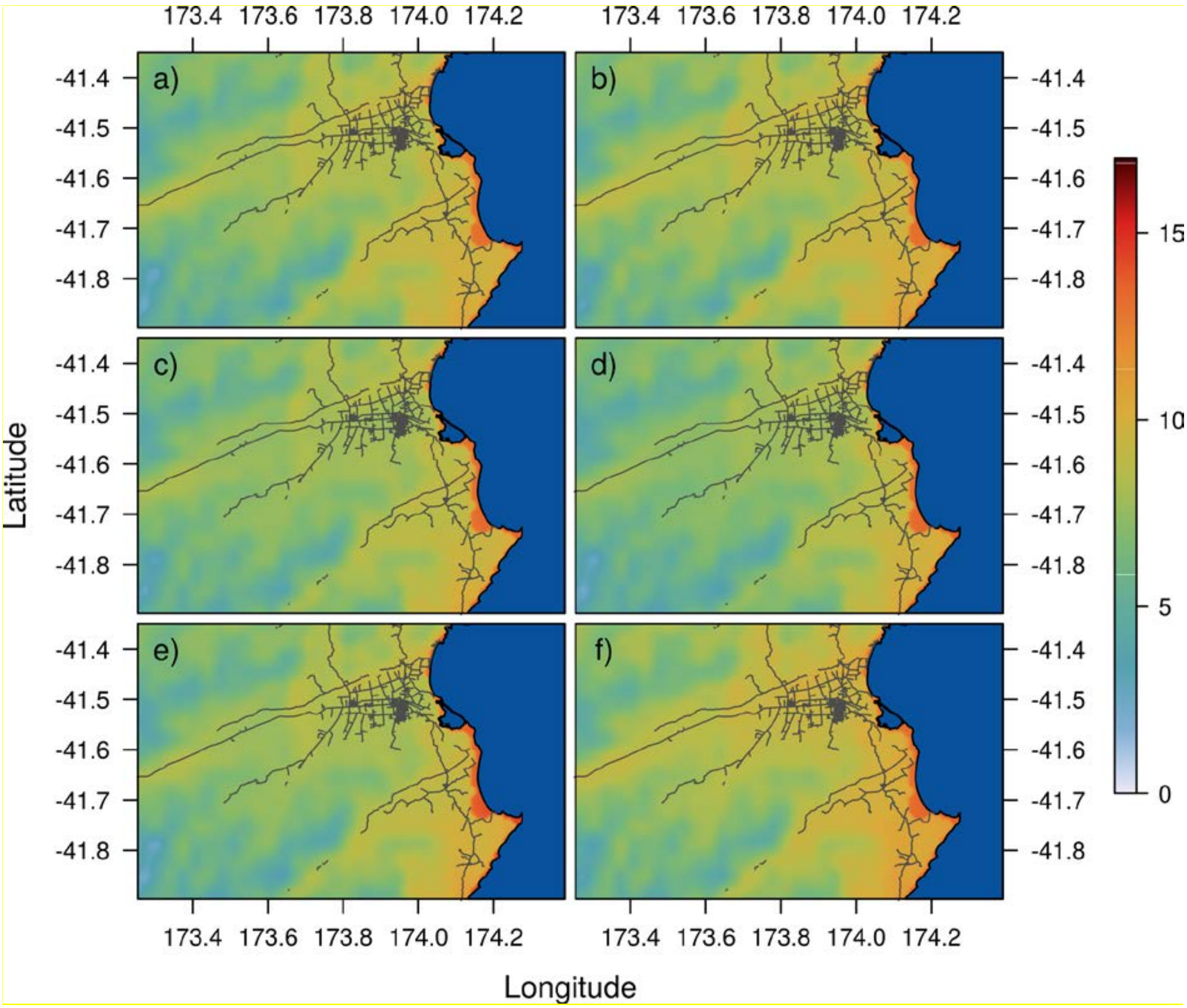

Figure A2: Maps of daily average minimum temperature (ºC) over the growing season (1 October to 30 April) for the Marlborough region using WRF output for a) 2008-9, b) 2009-10, c) 2010-2011, d) 2011-2012, e) 2012-2013, f) 2013-14.

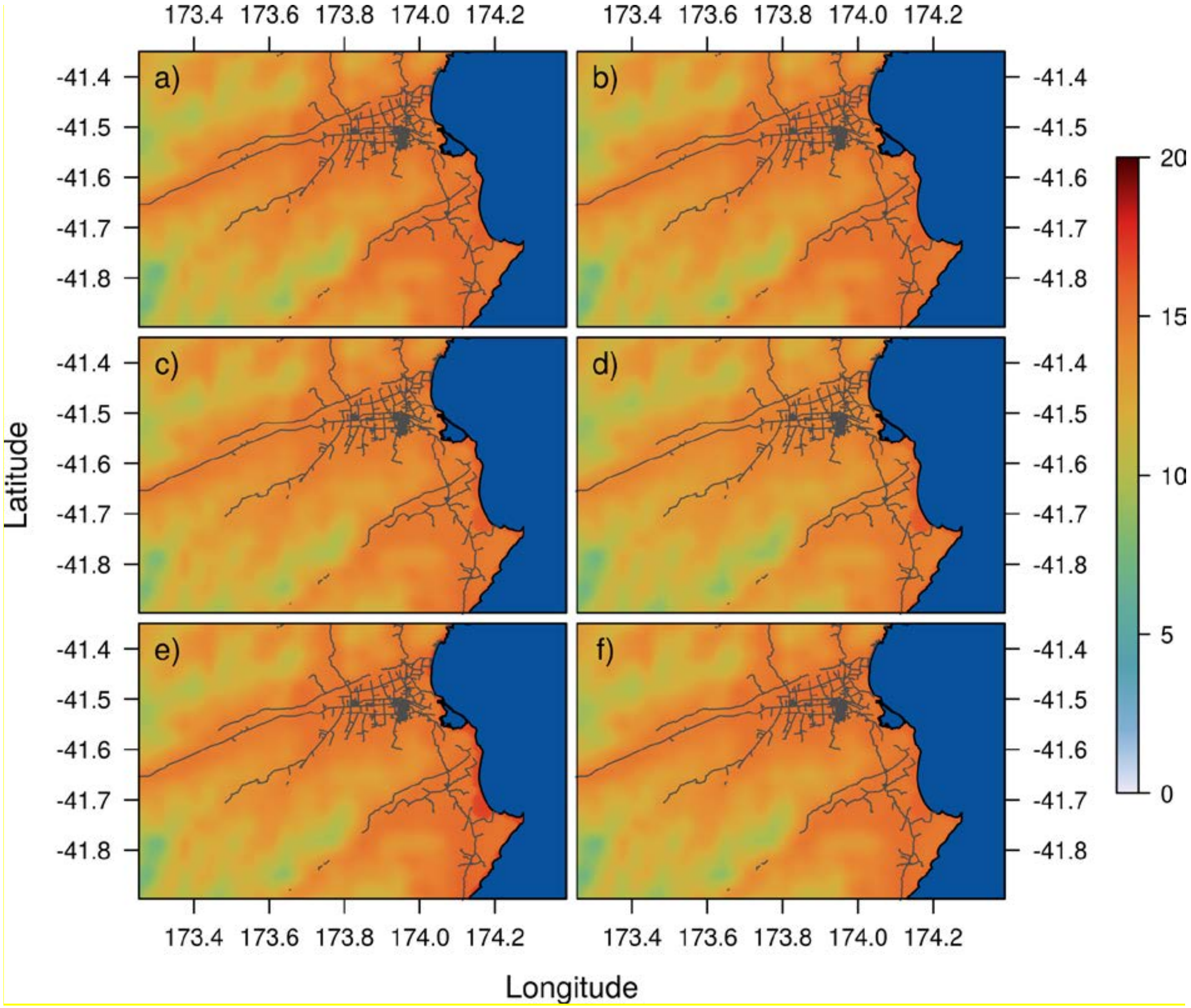

Figure A3: Maps of average growing season temperature (GST – ºC) over the growing season (1 October to 30 April) for the Marlborough region using WRF output for a) 2008-9, b) 2009-10, c) 2010-2011, d) 2011-2012, e) 2012-2013, f) 2013-14.

Appendix B: Bioclimatic index maps of the growing seasons from 2008-9 to 2013-14

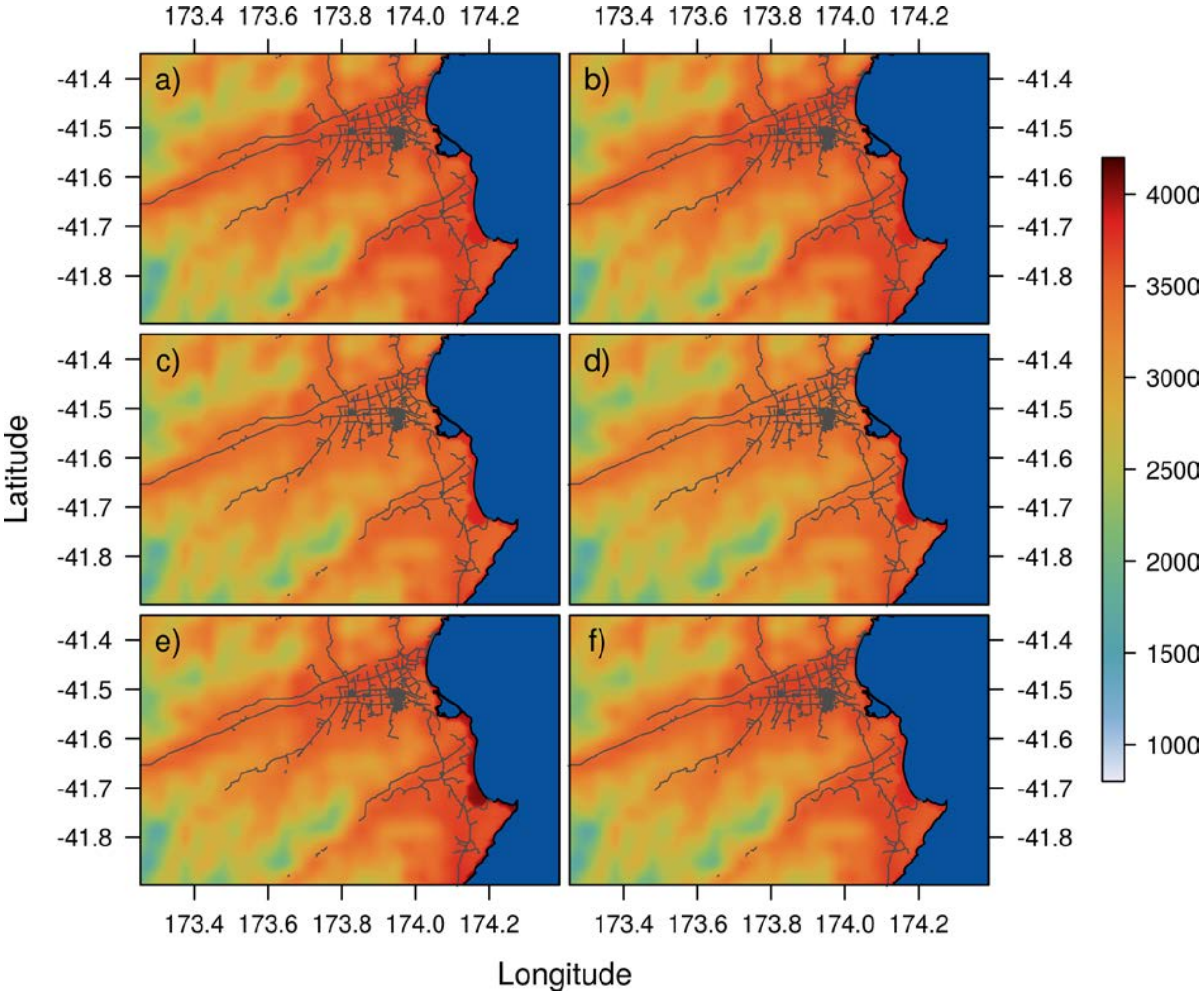

Figure B1: Maps of growing degree-day accumulation for the Marlborough vineyard region over the growing season based on Weather Research and Forecasting model temperatures for a) 2008-9, b) 2009-10, c) 2010-2011, d) 2011-2012, e) 2012-2013, f) 2013-14 derived using the Grapevine Flowering Véraison model (period = 29 August to 30 April, threshold = 0ºC).

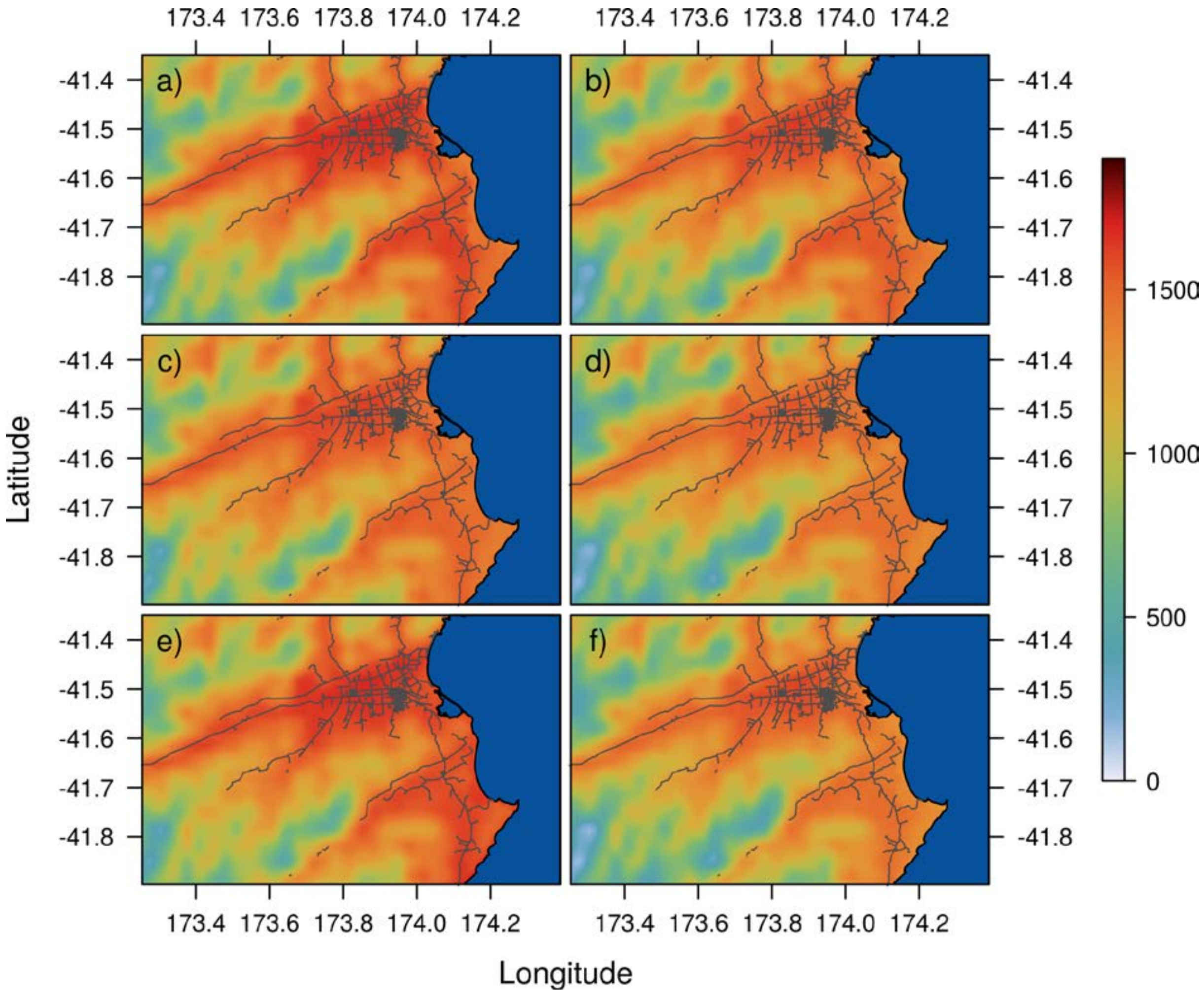

Figure B2: Maps of the Huglin Index for the Marlborough vineyard region over the growing season based on Weather Research and Forecasting model temperatures for a) 2008-9, b) 2009-10, c) 2010-2011, d) 2011-2012, e) 2012-2013, f) 2013-14 (period = 1 October to 31 March, threshold = 10ºC).

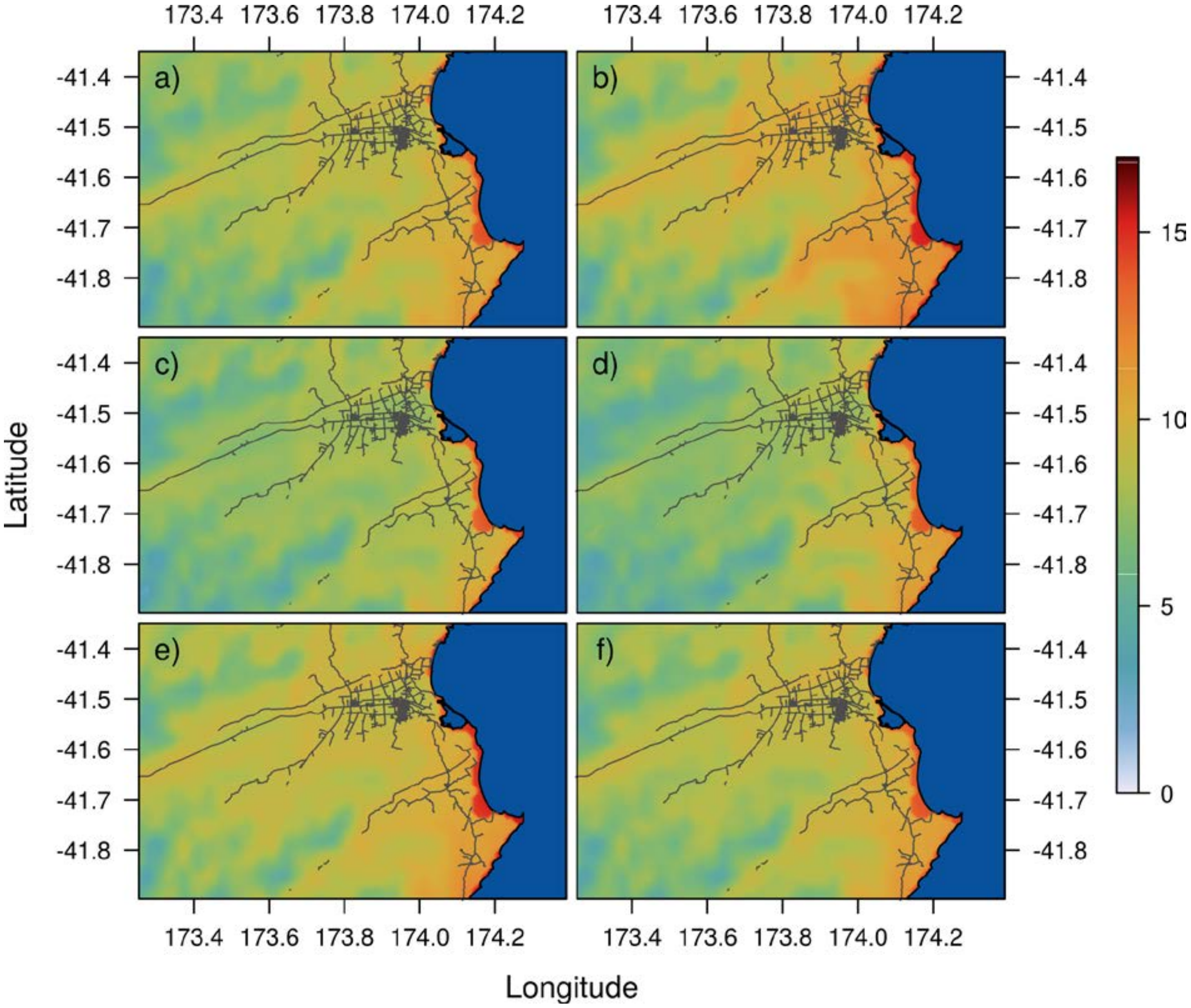

Figure B3: Maps of the Cool Nights index for the Marlborough vineyard region over the growing season based on Weather Research and Forecasting model temperatures for a) 2008-9, b) 2009-10, c) 2010-2011, d) 2011-2012, e) 2012-2013, f) 2013-14 (March average minimum temperature).

Appendix C: Maps of dates of flowering and veraison for Sauvignon blanc for the growing seasons from 2008-9 to 2013-14

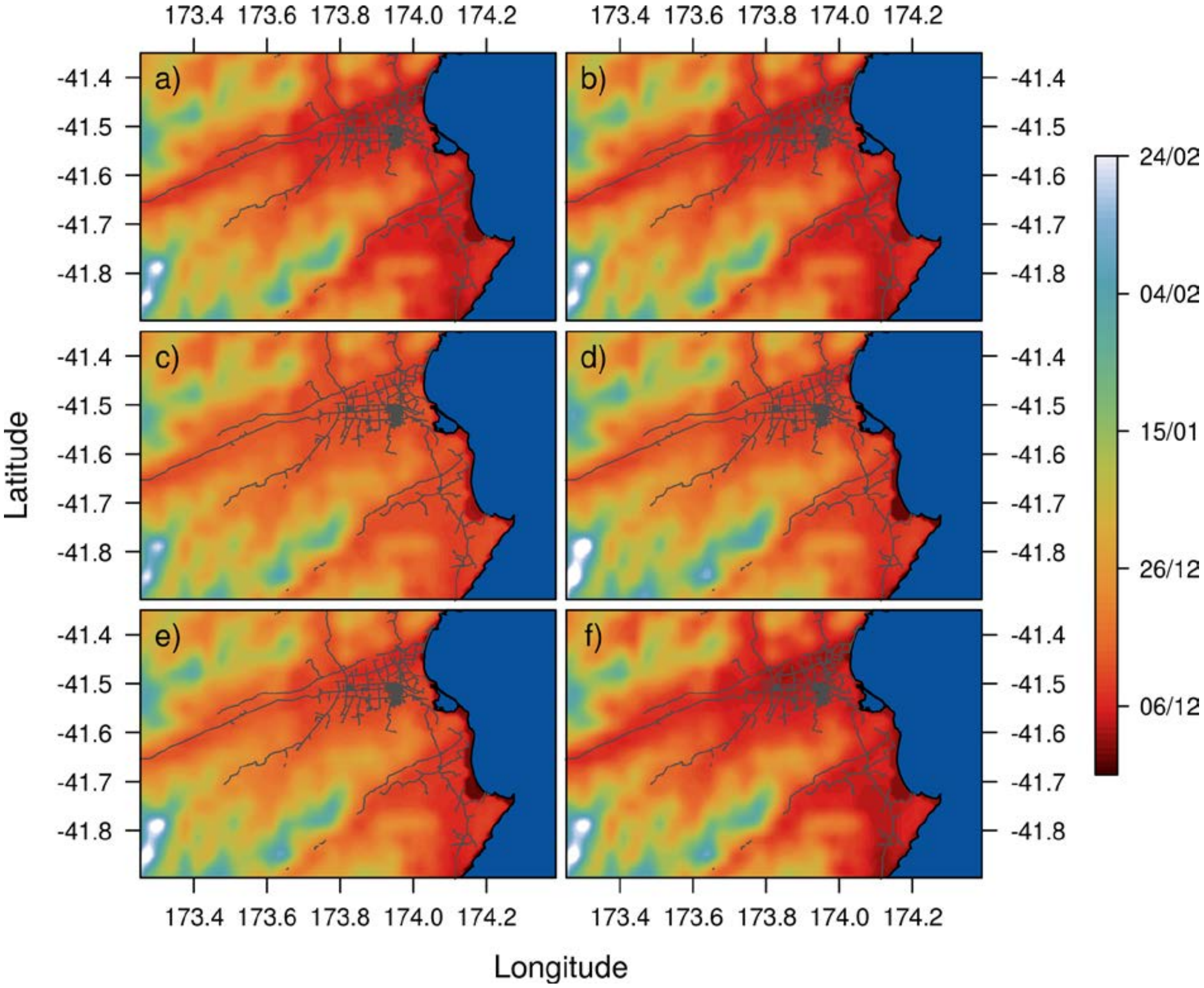

Figure C1: Maps of the predicted dates of flowering for Sauvignon blanc for the Marlborough region based on WRF temperatures at 1 km resolution over the growing seasons a) 2008-9, b) 2009-10, c) 2010-2011, d) 2011-2012, e) 2012-2013, f) 2013-14, based on the GFV F* value of 1282.

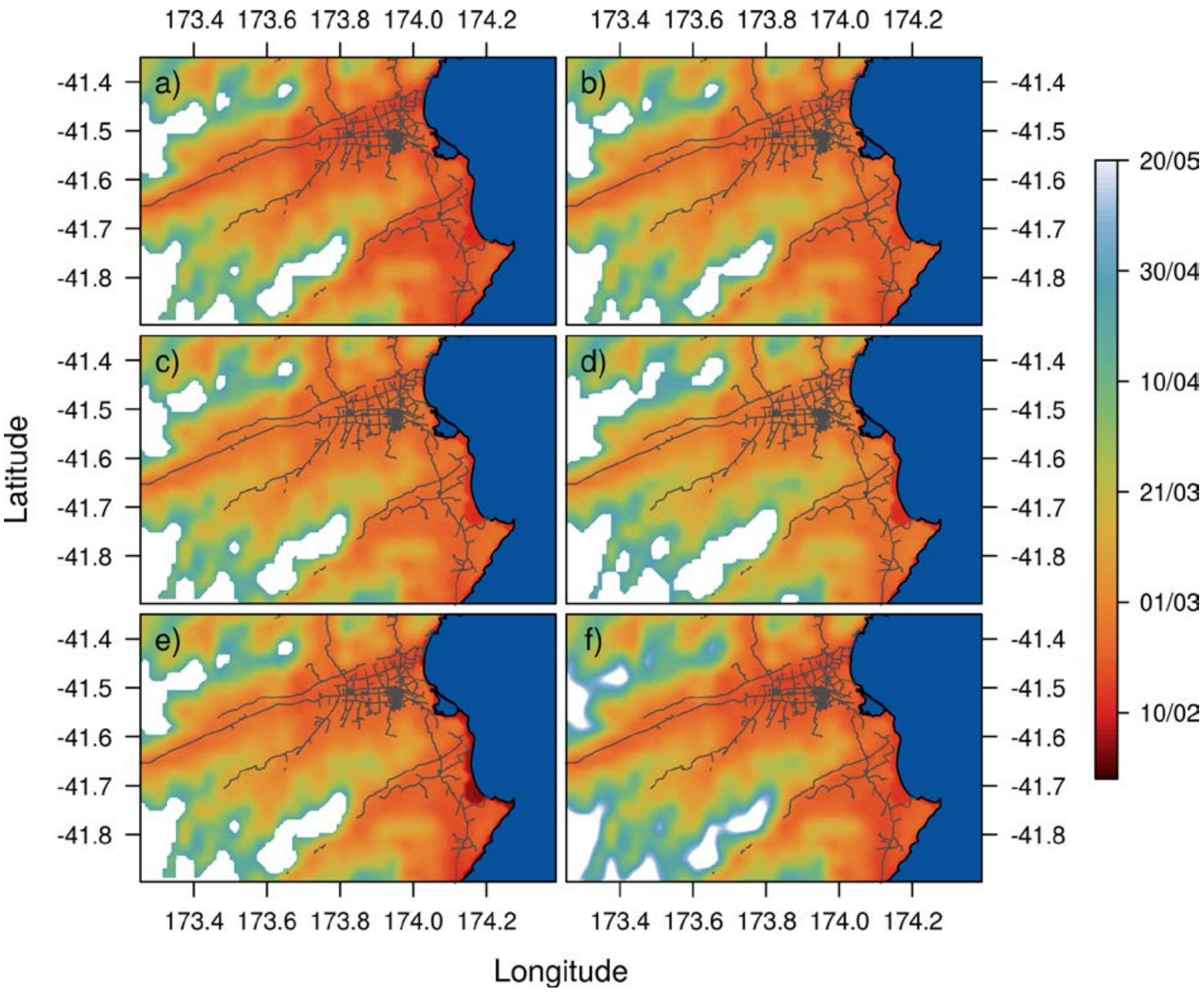

Figure C2: Maps of the predicted dates of véraison for Sauvignon blanc for the Marlborough region based on WRF temperatures at 1 km resolution over the growing seasons a) 2008-9, b) 2009-10, c) 2010-2011, d) 2011-2012, e) 2012-2013, f) 2013-14, based on the GFV F* value of 2528.

Appendix D: Examples of recent frost damage in the Marlborough vineyard region

Figure D1: Spring frost damage to a Marlborough vineyard.

Figure D2: Autumn frost damage.