Spatial analysis of climate in winegrape-growing regions in Australia

A. HALL[1,2] and G.V. JONES[3]

[1] National Wine and Grape Industry Centre, Charles Sturt University, Wagga Wagga, NSW 2678, Australia
[2] School of Environmental Sciences, Charles Sturt University, PO Box 789, Albury, NSW 2640, Australia
[3] Department of Environmental Studies, Southern Oregon University, Ashland, OR 97520, USA
Corresponding author: Dr Andrew Hall, fax +61 2 6051 9897, email ahall@csu.edu.au

Abstract

Background and Aims: Temperature-based indices are commonly used to indicate long-term suitability of climate for commercially viable winegrape production of different grapevine cultivars, but their calculation has been inconsistent and often inconsiderate of within-region spatial variability. This paper (i) investigates and quantifies differences between four such indices; and (ii) quantifies the within-region spatial variability for each Australian wine region.

Methods and Results: Four commonly used indices describing winegrape growing suitability were calculated for each Australian geographic indication (GI) using temperature data from 1971 to 2000. Within-region spatial variability was determined for each index using a geographic information system. The sets of indices were compared with each other using first- and second-order polynomial regression. Heat-sum temperature indices were strongly related to the simple measure of mean growing season temperature, but variation resulted in some differences between indices.

Conclusion: Temperature regime differences between the same region pairs varied depending upon which index was employed. Spatial variability of the climate indices within some regions led to significant overlap with other regions; knowledge of the climate distribution provides a better understanding of the range of cultivar suitability within each region.

Significance of the Study: Within-region spatial variability and the use of different indices over inconsistent time periods to describe temperature regimes have, before now, made comparisons of climates between viticulture regions difficult. Consistent calculations of indices, and quantification of spatial variability, enabled comparisons of Australian GIs to be made both within Australia and with American Viticultural Areas in the western United States.

Abbreviations

AVA American viticultural Area; **BEDD** biologically effective degree-days; **GDD** growing degree-days; **GI** geographic indication; **GST** growing season temperature; **HI** Huglin Index.

Keywords: *Australian geographic indication, climate, degree-day, viticulture, wine*

Introduction

Air temperature during the growing season is considered one of the most important factors in quality winegrape production. Temperature characteristics of wine-producing regions have been repeatedly studied and quantified in many different ways. One of the consequences of these disparate studies is a lack of consistent data describing temperature-related winegrape-growing conditions that can be directly compared between regions and countries. This paper describes the temperature regimes of Australian winegrape-growing regions (geographic indications (GIs)) as described by the Australian Wine and Brandy Corporation (2008) with the addition of two further regions, North and South Tasmania (Figure 1). Four temperature-derived indices using the same calculation method used in a recent publication that similarly described the temperature regimes of winegrape-growing regions of the western United States have been calculated (Jones et al. 2010). Similar efforts are underway to describe the winegrape-growing region climates of other parts of the globe (Jones et al. 2009). With these data, the Australian growing conditions can be directly compared with those of the western United States and, in the near future, with those of other regions.

In addition to enabling comparisons to be drawn across regions, the data presented in this paper estimates the range of index values within individual regions that occur because of spatial variability. Common practice in

doi: 10.1111/j.1755-0238.2010.00100.x

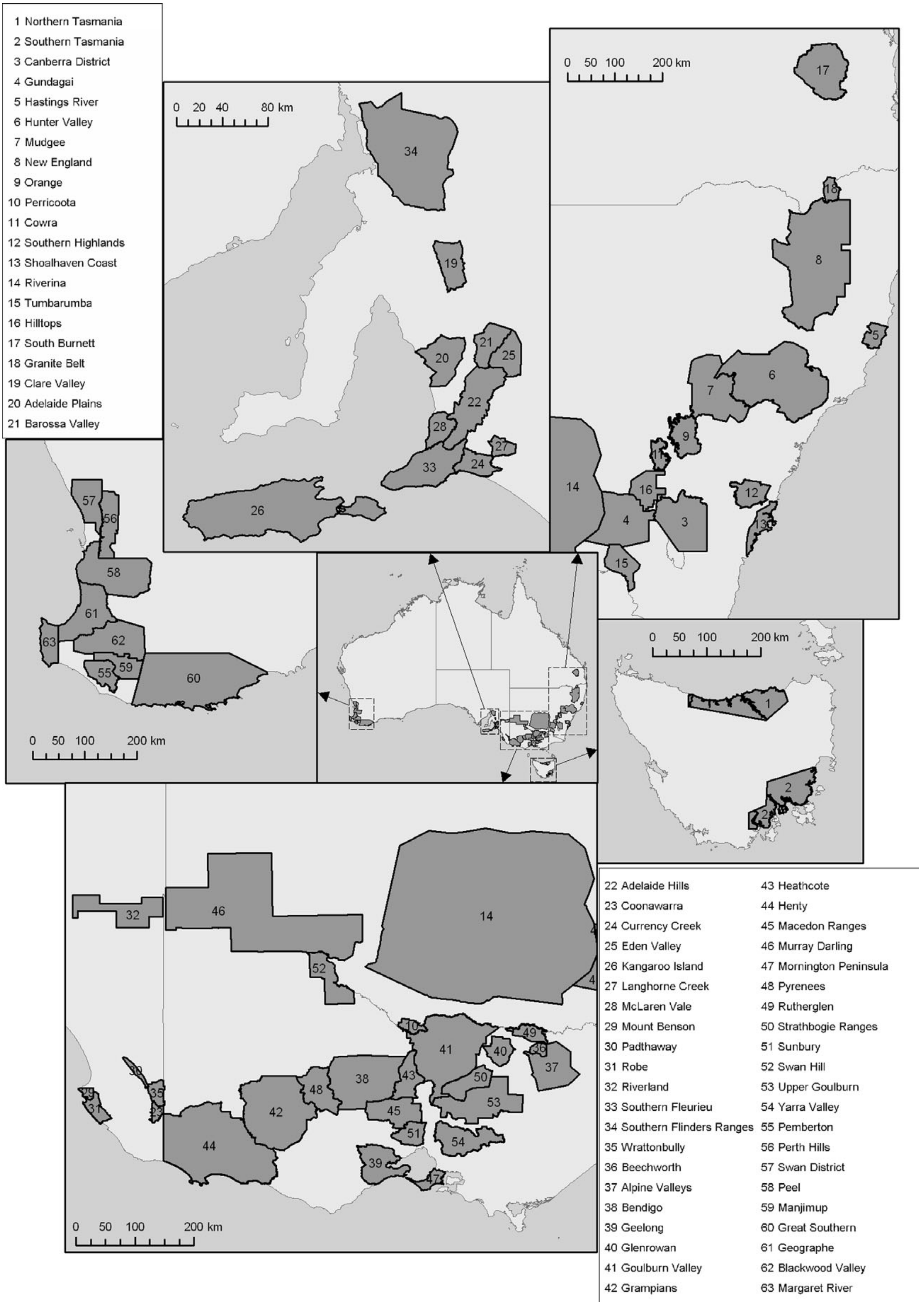

Figure 1. Australian geographic indications (GIs). Note: North and South Tasmania regions used in this study are not officially established GIs, but created by the authors from existing map sources and known areas of vineyards. (Data Source: Australian Wine and Brandy Corporation 2008).

Table 1. Climate variables derived, and the median index classification frequencies of the Australian geographical indications.

Variable	Equation	Months	Class limits†	Count	Frequency (%)
Average GST	$$\frac{\sum_{d=1}^{n}[T_{max}+T_{min}]/2}{n}$$	1 October–30 April	Too cool <13°C	0	0
			Cool = 13–15°C	2	3.2
			Intermediate = 15–17°C	14	22.2
			Warm = 17–19°C	28	44.4
			Hot = 19–21°C	16	25.4
			Very hot = 21–24°C	3	4.8
			Too hot >24°C	0	0
GDD‡	$$\sum_{d=1}^{n}\max[(T_{max}+T_{min})/2-10,0]$$	1 October–30 April	Too cool <850	1	1.6
			(Region I) 850–1389	5	7.9
			(Region II) 1389–1667	24	38.1
			(Region III) 1667–1944	16	25.4
			(Region IV) 1944–2222	10	15.9
			(Region V) 2222–2700	7	11.1
			Too hot >2700	0	0
HI	$$\sum_{d=1}^{n}\max[(T_{mean}-10+T_{max}-10)/2,0]K$$ where K is an adjustment for latitude/day length§	1 October–31 March	Too cool <1200	0	0
			Very cool = 1200–1500	2	3.2
			Cool = 1500–1800	8	12.7
			Temperate = 1800–2100	22	34.9
			Warm temperate = 2100–2400	12	19.1
			Warm = 2400–2700	14	22.2
			Very warm = 2700–3000	5	7.9
			Too hot >3000	0	0
BEDD	$$\sum_{d=1}^{n}\min[\max([T_{max}+T_{min}]/2-10,0)K+TR_{adj},9]$$ where $$TR_{adj}=\begin{cases}0.25[Tmax-Tmin-13], & [Tmax-Tmin]>13\\ 0, & 10<[Tmax-Tmin]<13\\ 0.25[Tmax-Tmin-10], & [Tmax-Tmin]<10\end{cases}$$ and K is an adjustment for latitude/day length§	1 October–30 April	<1000	2	3.2
			1000–1200	4	6.4
			1200–1400	22	34.9
			1400–1600	22	34.9
			1600–1800	12	19.1
			1800–2000	1	1.6
			>2000	0	0

†Note that the class names given in the table are not directly comparable (e.g. GST cool does not necessarily compare with HI cool). ‡Note that the GDD classes are based upon rounded °F limits as defined by Winkler et al. (1974) (in parentheses), which produce non-rounded classes in °C units. §K is a latitude coefficient that takes into account increasing day lengths starting from 1.0 at 34° increasing incrementally pole ward and is based upon day lengths using Julian day and latitude. GST, growing season temperature; GDD, growing degree-days; HI, Huglin Index; BEDD, biologically effective degree-days.

the past has been to select a climate station representative of a region and calculate temperature indices for that location. Here, temperature data were interpolated (i.e. estimated from point data to produce a continuous surface) to cover all the climate regions with a resolution of 0.05 decimal degrees (~26 km^2 at 35°S). Index values were then calculated for every one of the smallest resolvable areas (known as pixels) within the winegrape-growing regions. Summary data were then calculated to describe the spatial variability that occurs within each of the regions.

The four climate indices chosen for the analysis are described in Table 1. The indices discussed in this paper are simple indicators of the long-term suitability of a climate for the successful commercial production of winegrapes. Because of their simplicity, there will be climate types classified as suitable by these indices, while, in reality, aspects of their climates may make them unsuitable for commercial winegrape production. For example, flowering grapevines in highly continental climates that are subject to high levels of air mass variability may be persistently decimated by spring frosts despite having a warm growing season. Alternatively, extreme heat events during the ripening period may regularly occur, but high temperature variability results in the average temperature falling within a suitable classification category. Further terroir considerations, such as slope and aspect that can change solar radiation loading at a particular site or cultural practices evolved to deal with cool or hot climate conditions, can also extend the suitability range.

Growing season temperature (GST) is the simplest of the indices: the mean air temperature of all days between 1 October and 30 April. Because temperature is generally recorded as minimum and maximum temperatures each day, GST is an estimate of the average temperature. Actual average temperature (i.e. the average of a constantly recorded temperature) may vary a little from this estimate (McIntyre et al. 1987). In general terms, GSTs between 13 and 21°C are considered suitable for quality winegrape production with different varieties being more suitable to different temperature regimes (Jones 2006).

The growing degree-days (GDD) index is a measure of heat summation. The accumulation of heat units over time is a common method of describing the suitability of growing crops in different climates. It is calculated by subtracting a base temperature (10°C for winegrapes) from the average temperature recorded each day from 1 October to 30 April (in the Southern Hemisphere) and then summating all values above zero. The first extensive use of heat unit calculation for viticulture was conducted by Winkler et al. (1974) for California. The region classifications originally determined by Winkler et al. (1974) have been retained in this study (Table 1). However, no upper or lower bounds to these classifications were originally specified. Any climate with a seasonal accumulation of less than 1389°C-days was classified as Region I, and any climate with a seasonal accumulation of more than 2222°C-days was classified as Region V. Upper and lower limits to quality winegrape production are used in this paper based on observations made by Jones et al. (2010) in the western United States winegrape-growing regions, with a *Too Cold* class for GDD totals below 850°C-days and a *Too Hot* class for GDD totals above 2700°C-days. Note that these limits are not absolute and may not be applicable everywhere.

The Huglin Index (HI) (Huglin 1978) is a variation on the GDD, differing in three ways. Instead of using average temperature over a 24-hour period, the HI effectively uses an estimate of the daytime temperature by taking the mean of the average and maximum temperatures in its calculation. The daytime temperature may be considered to be of greater interest in terms of predicting plant growth, because this is the time during which photosynthesis occurs (Went 1957). In addition, a length of day ('longueur du jour') coefficient, K, is incorporated into the calculation, which Huglin (1978) varied from 1.02 to 1.06 at 40° to 50° latitude. Finally, HI is calculated using a 6-month period (1 October to 31 March, for the Southern Hemisphere) rather than a 7-month period used in the calculation of the other indices. For regions with high annual temperature ranges, indices calculated using a 7-month period are likely to have a lower index value than if using the 6-month period, because April temperatures are likely to be the coolest of the 7-month period. Indices calculated for areas that experience greater annual ranges in temperature will be more greatly modulated by including this cooler seventh month. Thus by using the 6-month period, the effect on the index of the magnitude of the annual temperature range is reduced.

The biologically effective degree-day (BEDD) index (Gladstones 1992) is another variant on calculating heat summation. It incorporates both an adjustment for diurnal temperature range and a day length correction similar to the HI, but by using different methods. Instead of estimating the daytime temperature as used in the HI, the BEDD index incorporates a factor based directly on the diurnal temperature range; the index is adjusted upward if the diurnal temperature range is greater than 13°C, and downward if less than 10°C (see Table 1). The factor adjusting for day length is similar, but slightly different to HI's K, varying from 1.00 at 40° of latitude to 1.045 at 50°. The BEDD index differs additionally from the HI in terms of it using the standard 7-month period (1 October to 30 April), thus retaining the potentially modulating effect on the index caused by variations in annual temperature ranges.

Methods

Temperature and elevation data

Decadal-scale climatic variability results in indices describing viticultural growing conditions varying over time. Comparisons made between regions using ad hoc calculations, particularly between regions in different countries, can result in indices being derived using data from unlike time periods. A common time period for the assessment of climate indices enables comparisons to be made spatially only, without the confounding effect of climatic temporal variability. A common period of 30 years, from 1971 to 2000, is used here, same as the reference period employed in the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC 2007). Interpolated maximum and minimum temperature grids (0.05 decimal degree resolution) generated for Australia were acquired from the Australian Bureau of Meteorology website (Bureau of Meteorology 2010) for each day from 1 October to 30 April for the years 1971 to 2000. A high resolution (3 arc-second) digital elevation map of Australia was also acquired (Jet Propulsion Laboratory 2004).

Index calculations

A grid of GST was simply calculated as the mean of all the daily temperature surfaces. The temperature grids where then used to calculate the three climate indices (GDD, HI and BEDD) per Table 1. Each index was calculated for the whole of Australia retaining the 0.05 decimal degree resolution. All the daily maps for each index were summed, then averaged by the total number of years to produce mean annual index totals for GDD, HI and BEDD, and averaged by the total number of days to produce mean GST (Figure 2). Pixels, whose centroid geographic coordinates were within a geographic indication (Australian Wine and Brandy Corporation 2008), were extracted from the digital elevation model and the four index maps,

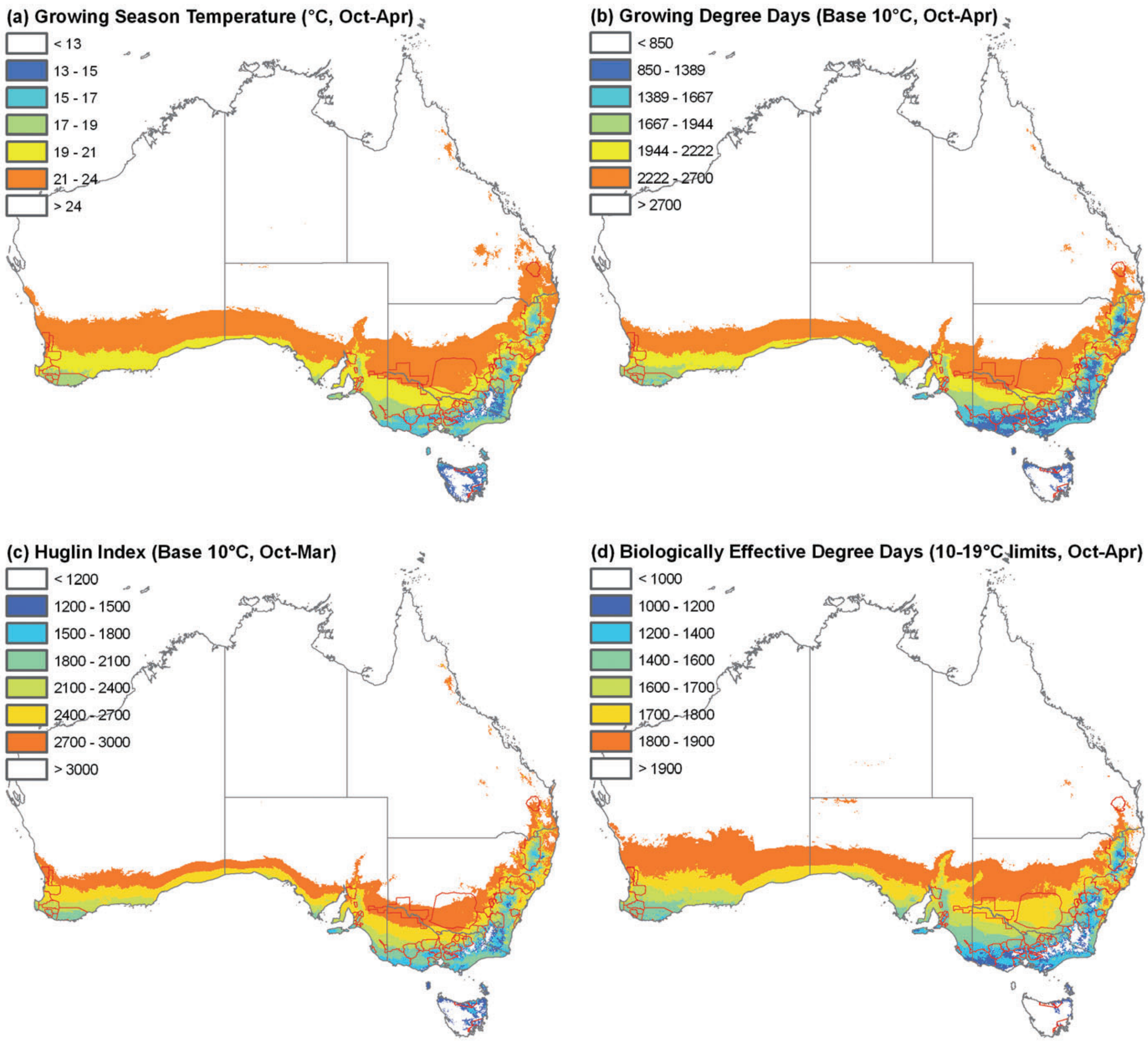

Figure 2. Maps of (a) growing season average temperatures, (b) growing degree-days, (c) the Huglin Index and (d) biologically effective growing degree-days, for Australia, 1971–2000. Geographical indication outlines are superimposed in red onto each map.

creating spatially appropriate data to assess the statistical properties of each GI's elevation and climate. The data describing the indices of the set of pixels extracted from each GI were summarised by five values: the maximum and minimum, the median (the second quartile), and the first and third quartiles (Table 3).

A common feature of both the HI and the BEDD is a latitude correction factor, which effectively adjusts the indices to account for differences in day length. Longer day lengths result in a greater proportion of a 24-h period being closer to the maximum recorded temperature than the minimum recorded temperature. Because the daily average temperature is actually an estimate based on the mean of the minimum and maximum temperatures, the latitude correction factor increases the index value to account for the extra heat accumulation that results from longer day lengths that occur at higher latitudes during summer. The HI latitudinal correction (K) was developed for the latitudes of European viticulture as a linear response to increasing day lengths at higher latitudes (Huglin 1978). Equations to calculate day length used in this analysis are given by Glarner (2006). Day lengths (in hours) at latitude, *Lat*, for Julian day, *Jday*, were calculated using the exposed radius part between the sun's zenith and the sun's circle, m:

$$dayLength_{Lat,JDay} = \frac{\arccos\left(1 - m_{Lat,JDay}\right)}{\pi} \cdot 24 \qquad (1)$$

where

$$m_{Lat_{Jday}} = 1 - \tan(Lat) \cdot \tan\left(Axis \cdot \cos\left[\frac{\pi \cdot Jday}{182.625}\right]\right) \qquad (2)$$

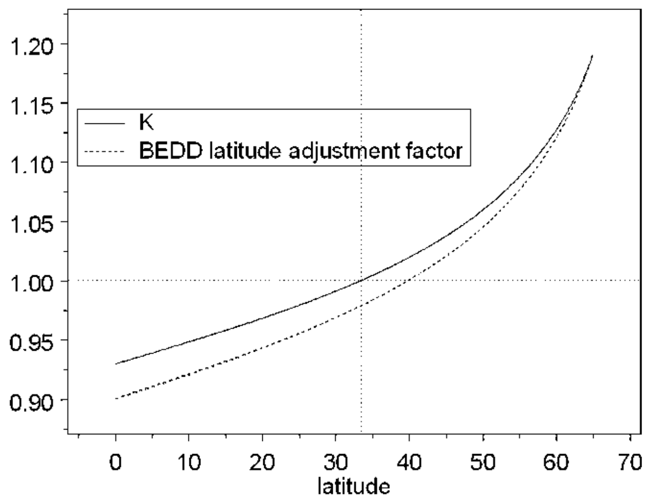

Figure 3. Comparison of Huglin's (*K*) and Gladstones's latitude adjustment factor for viticulture heat summation calculations. BEDD, biologically effective growing degree-days.

where *Axis* is the obliquity of the ecliptic (currently, ~0.409 rad), and *JDay* is the Julian day assumed to begin on 21 June (Southern Hemisphere).

The total length of daylight for the 6-month period 1 October (Julian Day 103) to 31 March (Julian Day 284) at a given latitude ($\text{totalSeasonDayLength}_{\text{Lat}}$) is

$$totalSeasonDayLength_{Lat} = \sum_{Jday=103}^{284} dayLength_{Lat_{JDay}} \quad (3)$$

Using the upper and lower values of K given by Huglin and Schneider (1998), i.e. $K_{40°} = 1.02$, $K_{50°} = 1.06$, and equivalent $totalSeasonDayLength_{Lat}$, an equation describing K as a function of *totalSasonDayLength* was derived using least squares:

$$K_{Lat} = 2.8311 \times 10^{-4} \cdot totalSeasonDayLength_{Lat} + 0.30834 \quad (4)$$

K for latitudes 0–65° at 0.05° intervals was then calculated. K, calculated in this way, is less than unity at latitudes lower than 33.3° (reaching 0.930 at the Equator). In this study, where K was less than unity, the latitude adjustment was not applied.

Gladstones's (1992) adjustment for latitude/day length is functionally similar to K (Figure 3). A first-order linear function describes the relationship between the two parameters ($R^2 \approx 1$):

$$BEDDLatitudeAdjstmentFactor = 1.1135K - 0.13520 \quad (5)$$

Although, both adjustment factors were based on day length/latitude, their respective magnitudes seem to have been decided arbitrarily. However, because this is an index, the absolute values derived are less important than the relative differences that the adjustment factors engender. The steeper gradient of the function of *BEDDLatitudeAdjustmentFactor* with respect to latitude (Figure 3) causes it to have a greater impact on heat sum calculation than K. The calculations used in this study have employed K as the latitude adjustment element for both heat sum calculations. This effectively modifies Gladstones's original BEDD, slightly reducing the effect of latitude in its calculation.

Results

The extracted elevation and index data are summarised by GI using quartiles in Tables 2 and 3. Table 2 includes information on the area of each GI. The GIs range in size from the anomalously large Riverina at 77 980 km^2 (the next largest being New England at 26 940 km^2) to the smallest, Langhorne Creek, at 240 km^2. Elevation ranges of the GIs vary greatly. The average elevation range is 603 m, with the greatest elevation range occurring in Alpine Valleys with 1817 m and the lowest occurring in Perricoota with 42 m. Large elevation ranges result in large temperature ranges and consequent large ranges in the climate indices of individual GIs (Table 3). Alpine Valleys' GST ranged from 11.9 to 19.5°C (a range of 7.6°C) compared with Perricoota's GST that varied from 19.6 to 20.0°C (a range of 0.4°C). The average range in GST was 2.9°C, enough to cross two classification levels of GST (Table 1).

The distributions of each of Australia's wine regions' median index values, as they relate to the different categories of climate suitability, are presented in Table 1. The distribution of wine region median GST index values closely conform to a normal distribution, with the greatest number of regions (28) in the middle *warm* category (17 to 19°C), a similar number are in the two adjacent *intermediate* and *hot* categories (14 and 16 regions, respectively), and a few GIs were categorised as either *cool* or *very hot* (2 and 3 regions, respectively). No GI had a median GST below 13°C or above 24°C. Similar normal-shaped distributions were found for GDD, HI and BEDD. The distribution for median GDD (categories for which were originally developed for the relatively warmer climate of California) was slightly positively skewed, whereas median HI (categories for which were originally developed for the relatively cooler climate of France) and median BEDD values were slightly negatively skewed.

The indices calculated for all the regions are compared against each other in Figure 4. The figure qualitatively illustrates the level of linearity of the relationships and the level of similarity between the different indices by the degree of scatter of the points. For example, Figure 4 suggests that GST and GDD are functionally very similar, evidenced by the straight line formed by the points and by the low level of scatter. Linear relationships between GST, GDD and HI are apparent from Figure 4, whereas a curvilinear relationship exists between BEDD and the other three indices. Models describing the relationships between the indices are presented in Table 4. First-order polynomials were used to model the apparent linear relationships and second-order polynomials were used for the curvilinear relationships (i.e. those involving BEDD). Coefficients of determination (R^2) quantitatively describe the level of scatter of the points around the model or how

Table 2. Australian GI regions' area and elevation.

GI name	State	Area† (km²)	Elevation (m)				GI name	State	Area† (km²)	Elevation (m)			
			Median	Max	Min‡	Range				Median	Max	Min‡	Range
Adelaide Hills	SA	1 470	392	714	149	565	Mornington Peninsula	Vic	720	56	315	0	315
Adelaide Plains	SA	930	23	154	0	154	Mount Benson	SA	280	12	70	0	70
Alpine Valleys	Vic	3 630	510	1972	155	1817	Mudgee	NSW	9 740	564	1242	227	1015
Barossa Valley	SA	590	278	596	112	484	Murray Darling	NSW	25 810	60	134	19	115
Beechworth	Vic	400	475	1045	204	841	New England	NSW	26 940	962	1579	205	1374
Bendigo	Vic	7 380	212	748	107	641	Orange	NSW	3 420	835	1390	376	1014
Blackwood Valley	WA	7 240	258	379	35	344	Padthaway	SA	360	44	117	12	105
Canberra District	NSW	8 610	644	1419	264	1155	Peel	WA	9 640	282	592	0	592
Clare Valley	SA	690	401	609	190	419	Pemberton	WA	2 500	147	317	6	311
Coonawarra	SA	400	65	127	51	76	Perricoota	NSW	600	97	127	85	42
Cowra	NSW	1 460	324	527	262	265	Perth Hills	WA	4 040	270	573	10	563
Currency Creek	SA	470	12	286	0	286	Pyrenees	Vic	2 720	279	788	171	617
Eden Valley	SA	600	409	632	219	413	Riverina	NSW	77 980	123	540	66	474
Geelong	Vic	2 830	88	396	0	396	Riverland	SA	4 130	40	99	1	98
Geographe	WA	6 820	141	406	0	406	Robe	SA	900	6	68	0	68
Glenrowan	Vic	1 310	178	507	128	379	Rutherglen	Vic	980	169	592	122	470
Goulburn Valley	Vic	9 780	115	411	86	325	Shoalhaven Coast	NSW	2 190	60	702	0	702
Grampians	Vic	9 450	255	1161	142	1019	South Burnett	Qld	8 340	401	1141	169	972
Granite Belt	Qld	1 170	887	1298	604	694	Southern Fleurieu	SA	1 390	212	442	0	442
Great Southern	WA	20 440	181	1083	0	1083	Southern Flinders Ranges	SA	4 730	378	958	1	957
Gundagai	NSW	8 850	345	1168	179	989	Southern Highlands	NSW	2 690	638	906	54	852
Hastings River	NSW	1 530	46	649	0	649	Strathbogie Ranges	Vic	1 980	422	1044	144	900
Heathcote	Vic	1 910	210	599	112	487	Sunbury	Vic	1 270	160	494	0	494
Henty	Vic	14 760	124	458	0	458	Swan District	WA	4 480	62	283	0	283
Hilltops	NSW	3 110	465	713	249	464	Swan Hill	Vic	2 750	72	129	47	82
Hunter Valley	NSW	19 970	337	1597	0	1597	Tasmania North§	Tas	4 520	135	1177	0	1177
Kangaroo Island	SA	4 480	92	316	0	316	Tasmania South§	Tas	4 350	205	1264	0	1264
Langhorne Creek	SA	240	13	64	0	64	Tumbarumba	NSW	2 970	544	1290	209	1081
Macedon Ranges	Vic	2 820	507	1013	211	802	Upper Goulburn	Vic	5 160	389	1777	140	1637
Manjimup	WA	2 740	221	345	108	237	Wrattonbully	SA	760	89	145	41	104
Margaret River	WA	2 640	75	234	0	234	Yarra Valley	Vic	3 120	251	1338	17	1321
McLaren Vale	SA	440	113	417	0	417							

†Area is rounded to the nearest 10 km^2 and is approximate because of the grid-based estimation procedure. ‡GIs shown with minimum elevations of 0 may have areas a few metres below sea-level. §Tasmanian regions are not officially established GIs. GI, geographical indication.

accurately the formulae describe the relationship between the two indices.

Discussion

The greatest influences on differences in index values between GIs are latitude and continentality. Inland GIs are more likely to have greater index values than GIs proximal to the ocean at the same latitude. Although average temperatures are likely to be similar at coincident latitudes using data for whole years, the indices are calculated using temperature data from the summer months only. Summer temperatures deviate more from the annual average with increasing continentality. Daytime temperatures are also likely to be greater with increasing continentality. This increases the rate of change of HI with increasing continentality relative to the other indices, because HI uses an estimate of daytime temperature rather than average diurnal temperature. Latitude has the greatest influence on the indices between the regions. Lower latitudes experience warmer temperatures and consequently greater index magnitudes, leaving much of Australia deemed unsuitable for quality winegrape production based on these climate indices (Figure 2).

Historically, the seven (or six in the case of the HI) warmest months of the year have been used to assess suitability for winegrape growing. This provided the best indication of the lower suitability cut-off at the cool end of the climate scale (when using monthly mean temperature). Inclusion of months outside this range can result in a false unsuitable classification of some cool areas with continental climates where the summer months are significantly warmer than winter, early-spring and late-autumn months. In warm regions, however, budbreak often occurs well before 1 October and harvest can occur before February. The temporal extent of the actual growing season for such regions will therefore be quite different to the standard seven month period used to calculate GST. The temperature of the seven month period, nevertheless, can still be used as a guide to potential viticultural unsuitability due to excessive heat, because this figure will be directly related to the temperature of the actual growing season. Continuing use of the seven month period may therefore be considered appropriate in guiding long-term suitability of a climate for winegrape production. Calculating indices from a single time period is a simple, consistent method that can be applied to any location, whereas

Table 3. Australian GI 1971–2000 quartile statistics for average GST, GDD, HI and BEDD.

GI name	GST (°C)					GDD					HI					BEDD				
	Min	25%	Median	75%	Max	Min	25%	Median	75%	Max	Min	25%	Median	75%	Max	Min	25%	Median	75%	Max
Adelaide Hills	16.6	17.3	17.5	17.8	18.8	1343	1480	1530	1590	1805	1764	1945	1994	2027	2264	1126	1260	1297	1323	1458
Adelaide Plains	20.1	20.7	20.7	20.8	20.8	2072	2196	2209	2215	2225	2498	2568	2584	2591	2603	1600	1657	1663	1665	1667
Alpine Valleys	11.9	15.8	17.2	18.0	19.5	589	1213	1476	1637	1947	897	1763	2076	2252	2511	449	1138	1336	1445	1588
Barossa Valley	17.4	18.7	19.0	19.5	20.1	1516	1774	1852	1947	2064	2040	2272	2342	2411	2515	1288	1445	1489	1543	1601
Beechworth	14.6	16.4	17.7	18.2	18.9	1001	1330	1574	1681	1816	1452	1860	2155	2269	2434	898	1191	1375	1442	1532
Bendigo	15.9	17.9	18.5	19.0	19.6	1222	1621	1746	1846	1969	1772	2183	2291	2382	2506	1107	1394	1462	1518	1583
Blackwood Valley	18.0	18.5	18.9	19.1	19.5	1631	1745	1819	1861	1945	2053	2201	2294	2356	2451	1428	1500	1550	1573	1625
Canberra District	13.4	17.0	17.7	18.3	19.9	777	1428	1581	1691	2024	1293	1966	2115	2217	2524	775	1299	1398	1461	1627
Clare Valley	18.2	18.8	19.0	19.3	19.6	1682	1798	1847	1902	1974	2227	2322	2388	2423	2470	1405	1471	1505	1527	1564
Coonawarra	17.3	17.3	17.4	17.5	17.6	1479	1491	1511	1517	1544	1984	2026	2046	2062	2087	1301	1314	1330	1335	1355
Cowra	19.8	20.5	20.8	21.1	21.5	2013	2158	2222	2290	2375	2551	2698	2767	2842	2918	1634	1696	1725	1751	1776
Currency Creek	18.1	18.7	18.8	18.9	19.1	1641	1775	1795	1809	1854	2036	2107	2128	2154	2219	1379	1469	1481	1494	1526
Eden Valley	16.9	17.4	17.9	18.1	18.7	1420	1521	1611	1660	1775	1937	2047	2141	2189	2296	1219	1297	1361	1390	1458
Geelong	16.0	16.9	17.2	17.5	17.9	1211	1401	1466	1530	1615	1623	1763	1840	1918	2030	1075	1206	1257	1306	1381
Geographe	18.6	19.4	19.8	20.1	21.0	1756	1920	2008	2082	2261	2156	2369	2438	2490	2596	1518	1600	1636	1671	1725
Glenrowan	18.0	19.3	19.5	19.6	19.9	1644	1904	1937	1978	2033	2217	2481	2515	2552	2596	1409	1564	1585	1600	1623
Goulburn Valley	17.8	19.1	19.5	19.9	20.5	1591	1872	1942	2030	2166	2140	2404	2480	2579	2702	1377	1544	1580	1620	1673
Grampians	12.3	16.7	16.9	17.7	18.6	628	1356	1408	1580	1757	1082	1875	1943	2131	2316	578	1203	1240	1362	1474
Granite Belt	16.8	18.7	18.9	19.3	20.3	1375	1773	1821	1899	2118	1776	2154	2204	2291	2523	1278	1577	1606	1654	1766
Great Southern	16.5	18.2	18.4	18.5	19.1	1325	1673	1705	1744	1872	1675	1955	2019	2120	2256	1181	1429	1457	1489	1569
Gundagai	15.9	19.2	19.8	20.3	20.8	1222	1878	2020	2108	2221	1762	2454	2573	2662	2769	1136	1565	1620	1656	1695
Hastings River	18.5	21.0	21.2	21.5	21.8	1726	2267	2312	2364	2434	2013	2444	2490	2554	2658	1530	1824	1843	1865	1887
Heathcote	16.4	17.9	18.4	18.8	19.3	1318	1613	1709	1802	1900	1886	2171	2254	2337	2429	1191	1396	1452	1500	1550
Henty	15.6	16.5	16.7	16.9	17.7	1136	1309	1354	1396	1563	1429	1741	1803	1907	2125	937	1157	1193	1235	1367
Hilltops	18.3	19.2	19.5	19.8	20.5	1701	1880	1942	2006	2149	2280	2470	2528	2588	2707	1476	1574	1601	1633	1688
Hunter Valley	13.4	19.8	20.7	21.4	22.4	734	2003	2194	2353	2558	1133	2403	2592	2743	2924	640	1661	1748	1815	1882
Kangaroo Island	16.6	17.4	17.6	17.9	18.5	1330	1492	1551	1612	1732	1577	1720	1791	1846	1983	1100	1238	1294	1348	1458
Langhorne Creek	19.1	19.2	19.3	19.3	19.3	1856	1879	1894	1907	1911	2230	2265	2291	2309	2318	1531	1545	1556	1560	1573
Macedon Ranges	14.2	15.3	15.9	16.4	17.8	893	1095	1217	1313	1593	1358	1618	1743	1864	2179	803	1002	1094	1181	1388
Manjimup	18.0	18.3	18.4	18.6	18.8	1629	1691	1721	1749	1793	1991	2078	2127	2153	2223	1409	1452	1477	1494	1524
Margaret River	18.4	19.1	19.2	19.3	19.9	1702	1861	1887	1912	2031	1846	2052	2092	2139	2314	1444	1568	1584	1602	1666
McLaren Vale	17.2	18.7	19.1	19.2	19.6	1468	1777	1865	1886	1974	1897	2146	2197	2210	2285	1245	1442	1499	1512	1553
Mornington Peninsula	16.5	17.2	17.5	17.6	17.9	1316	1454	1514	1554	1603	1545	1689	1791	1854	1900	1046	1176	1243	1285	1318
Mount Benson	17.3	17.4	17.5	17.5	17.6	1474	1493	1512	1525	1548	1786	1812	1832	1860	1910	1253	1268	1289	1302	1330
Mudgee	15.9	18.5	19.6	20.5	21.6	1220	1736	1971	2155	2399	1680	2216	2456	2620	2871	1117	1504	1638	1715	1795
Murray Darling	20.9	21.5	21.7	22.1	22.8	2253	2364	2416	2505	2654	2770	2875	2914	2967	3110	1708	1743	1756	1782	1819
New England	14.7	17.0	18.1	19.7	22.6	960	1424	1650	1981	2603	1377	1896	2123	2452	3085	893	1350	1519	1698	1893
Northern Tasmania†	11.8	14.5	15.1	15.6	16.2	464	896	1034	1132	1256	853	1296	1427	1508	1700	419	839	975	1063	1187
Orange	15.9	16.6	17.6	18.4	19.7	1216	1367	1551	1730	2002	1698	1914	2084	2285	2551	1117	1276	1392	1510	1659
Padthaway	17.8	18.0	18.1	18.2	18.3	1589	1623	1657	1679	1697	2151	2181	2210	2223	2235	1387	1410	1433	1447	1453
Peel	19.1	19.9	20.2	20.9	21.9	1870	2035	2091	2243	2457	2354	2514	2577	2635	2760	1555	1630	1658	1716	1795
Pemberton	18.1	18.3	18.4	18.5	19.1	1648	1695	1722	1738	1860	1990	2027	2048	2088	2175	1417	1452	1469	1484	1567
Perricoota	19.6	19.7	19.8	19.9	20.0	1962	1994	2011	2027	2049	2521	2547	2563	2577	2597	1584	1598	1604	1610	1618
Perth Hills	20.1	20.9	21.4	21.8	22.4	2085	2236	2341	2429	2557	2517	2629	2740	2833	2945	1645	1705	1743	1772	1816
Pyrenees	15.1	17.3	17.8	18.4	19.0	1080	1481	1591	1712	1833	1604	2037	2146	2275	2393	980	1293	1366	1442	1513
Riverina	19.7	21.2	21.5	22.2	23.2	1988	2308	2380	2516	2725	2498	2821	2877	2993	3185	1571	1711	1736	1777	1825
Riverland	20.5	21.0	21.2	21.4	21.9	2149	2255	2305	2345	2451	2719	2789	2827	2855	2929	1691	1727	1744	1755	1782
Robe	17.1	17.2	17.3	17.3	17.5	1431	1461	1474	1491	1528	1715	1773	1789	1842	1889	1197	1230	1246	1270	1311
Rutherglen	18.5	19.4	19.7	20.0	20.2	1734	1927	1991	2044	2094	2322	2525	2591	2631	2675	1468	1578	1610	1630	1650
Shoalhaven Coast	17.8	19.4	19.8	20.1	20.5	1577	1920	2006	2082	2157	1919	2153	2228	2278	2422	1389	1611	1654	1696	1743
South Burnett	20.9	22.5	22.9	23.4	24.5	2246	2579	2673	2780	3013	2570	2882	2976	3077	3277	1814	1912	1930	1942	1964
Southern Fleurieu	16.7	17.3	17.8	18.1	18.5	1350	1475	1580	1642	1739	1644	1828	1895	1969	2101	1124	1244	1320	1357	1423
Southern Flinders Ranges	18.5	19.8	20.4	21.0	22.9	1740	2017	2133	2255	2678	2333	2539	2629	2717	3008	1455	1589	1642	1692	1836
Southern Highlands	16.5	17.2	17.6	18.4	20.5	1311	1465	1552	1713	2152	1737	1935	2027	2143	2577	1199	1329	1397	1499	1739
Southern Tasmania†	7.3	13.3	14.1	14.8	15.6	97	695	837	965	1130	244	1121	1253	1390	1564	0	640	771	893	1046
Strathbogie Ranges	15.0	16.5	17.1	18.1	19.2	1063	1333	1452	1655	1877	1560	1880	2002	2208	2440	969	1196	1284	1417	1551
Sunbury	16.4	17.2	17.6	17.8	18.2	1299	1466	1552	1589	1680	1806	1935	2014	2036	2105	1159	1265	1341	1368	1407
Swan District	21.7	22.0	22.1	22.3	22.5	2413	2484	2501	2534	2583	2679	2763	2823	2872	2966	1775	1803	1811	1819	1834
Swan Hill	20.3	20.7	20.9	21.1	21.3	2121	2191	2238	2277	2325	2660	2718	2762	2805	2848	1651	1680	1699	1712	1729
Tumbarumba	14.2	16.5	17.3	18.1	19.1	920	1336	1496	1655	1864	1418	1933	2096	2280	2453	876	1252	1368	1475	1569
Upper Goulburn	12.7	16.2	17.1	17.5	18.3	678	1281	1451	1535	1698	1045	1816	2018	2117	2294	563	1160	1297	1360	1463
Wrattonbully	17.3	17.5	17.6	17.7	17.9	1486	1531	1554	1565	1600	2044	2091	2115	2124	2153	1314	1347	1362	1371	1393
Yarra Valley	12.4	15.6	16.6	17.4	18.4	623	1144	1343	1506	1708	963	1615	1810	1945	2114	479	1028	1179	1297	1427

†Tasmanian regions are not officially established GIs. GI, geographical indication; GST, growing season temperature; GDD, growing degree-days; HI, Huglin Index; BEDD, biologically effective degree-days.

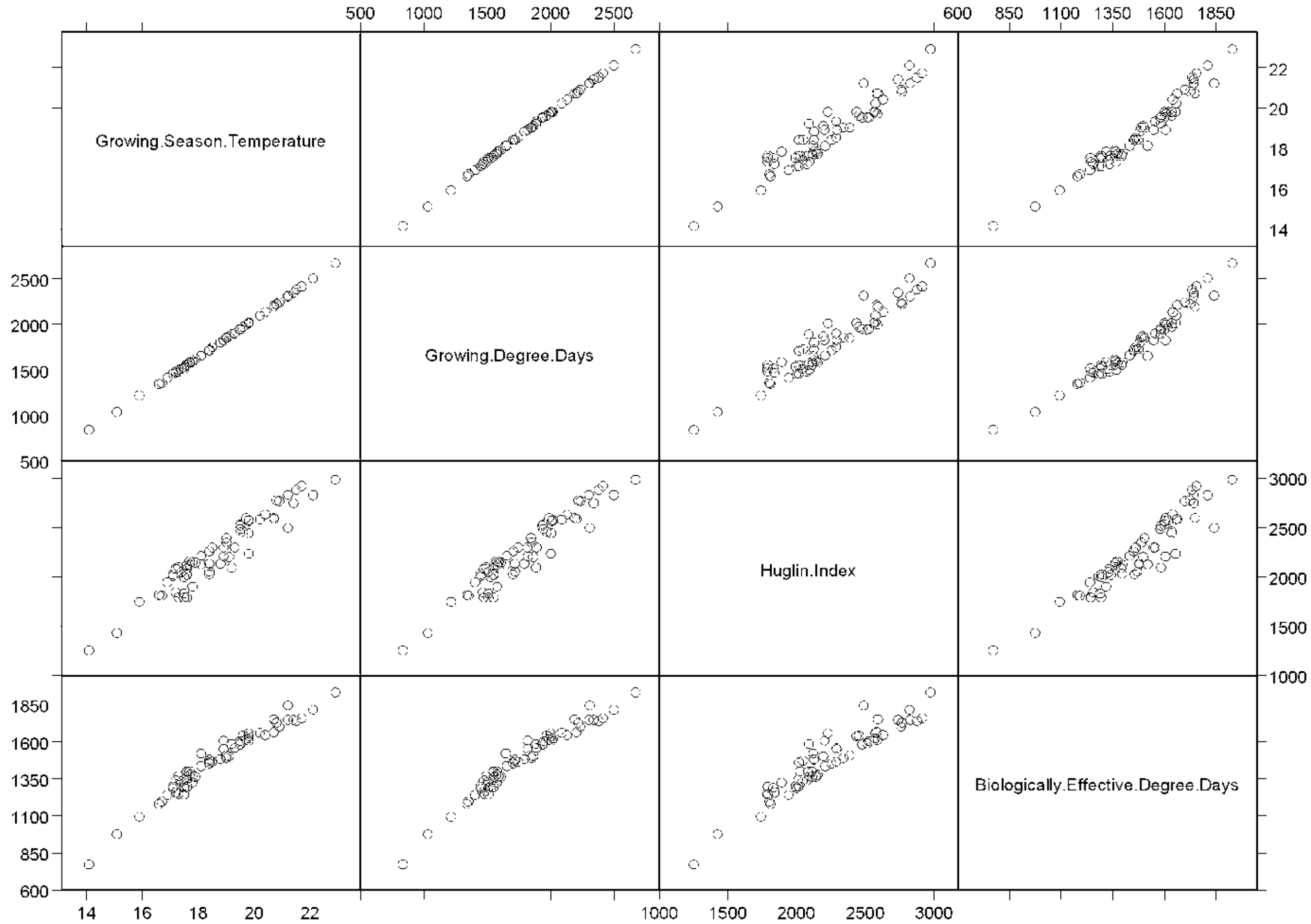

Figure 4. Scatter matrix illustrating relationships between geographical indication (GI) medians of each of the four indices. Each plotted circle represents one GI.

Table 4. Order of polynomial, coefficient of determination (R^2), and formula for each model describing relationships between the different indices.

Function	Order	R^2	Formula
$GST = f(GDD)$	1	0.9995	$GST = 4.78 \times 10^{-3}GDD + 10.2$
$GST = f(HI)$	1	0.9059	$GST = 4.51 \times 10^{-3}HI + 8.61$
$GST = f(BEDD)$	2	0.9641	$GST = 2.93 \times 10^{-6}BEDD^2 - 5.42 \times 10^{-4}BEDD + 13.0$
$GDD = f(GST)$	1	0.9995	$GDD = 209GST - 2.13 \times 10^3$
$GDD = f(HI)$	1	0.9092	$GDD = 0.946HI - 332$
$GDD = f(BEDD)$	2	0.9476	$GDD = 6.63 \times 10^{-4}BEDD^2 - 0.255BEDD + 690$
$HI = f(GST)$	1	0.9059	$HI = 201GST - 1.52 \times 10^3$
$HI = f(GDD)$	1	0.9092	$HI = 0.961GDD + 522$
$HI = f(BEDD)$	2	0.8845	$HI = 2.82 \times 10^{-4}BEDD^2 + 0.782BEDD + 460$
$BEDD = f(GST)$	2	0.9691	$BEDD = -7.31GST^2 + 397GST - 3370$
$BEDD = f(GDD)$	2	0.9710	$BEDD = -1.83 \times 10^{-4}GDD^2 + 1.25GDD - 142$
$BEDD = f(HI)$	2	0.8981	$BEDD = -1.57 \times 10^{-4}HI^2 + 1.26HI - 532$

GST, growing season temperature; GDD, growing degree-days; HI, Huglin Index; BEDD, biologically effective degree-days.

determining climate suitability indices from different time periods (e.g. before October in warm regions) for different locations and varieties would be impractical and lead to incomparability.

Australia has no upper latitudinal limit to viable viticulture. Only Southern Tasmania has marginal conditions based on its median index values (median GST = 14.1°C), although an upper GST of 15.6°C indicates Southern Tasmania has areas that fall within the intermediate GST category. Similarly, some of the warmest regions, such as South Burnett, Riverina and Hunter Valley with median GSTs of 22.9, 21.5 and 20.7°C, respectively, contain areas with significantly lower GSTs, indicated by minimum GSTs of 20.9, 19.7 and 13.4°C, respectively. These regions' combinations of large area and/or varied topography cause a high degree of absolute spatial variability in index values and therefore a wide range in cultivar suitability.

The large size of many of the GIs indicates there is scope for spatial variability within each region simply because of changes in latitude or continentality. The greatest effect on temperature variability within each GI is, however, topography. With a decrease in average temperature of 6.5°C per km of elevation (Donn 1975, Sturman and Tapper 1996) and an average elevation range of 603 m, mean temperature spatially varies by about 3.9°C on average within each of the GIs. The spatial variability within each GI is an important consideration when interpreting data in Table 3. The GIs with high median index values are likely to have their winegrape-growing regions in areas that experience the lower temperatures, such as South Burnett, Riverina and Hunter Valley, thus a more accurate description of their temperature regimes may be described by an index closer to the first quartile. Conversely, GIs with low median index values are likely to have their vineyards sites in areas with relatively warmer temperatures, such as the higher latitude Tasmanian regions, or in regions that include large areas at high elevations, such as Alpine Valleys and Grampians. In such cases, the third quartile index may better describe the effective winegrape-growing temperature regime.

The value of knowledge of the full spatial range of indices within a GI can be illustrated with data from three example climate stations. Cape Naturaliste was one of two climate stations with a >95% complete temperature data set in the Margaret River GI for the 1971–2000 period. The range of values for the total GDD produced by the Bureau of Meteorology interpolated climate maps were 1702 to 2031°C-days. Using the climate data from the Cape Naturaliste climate station produced a GDD of 1880°C-days. Cape Naturaliste is located in the very northern-most part of the GI, which places it in a relatively warm location. In the range of GDD values for Margaret River, it is above the third quartile. As well as differences within GIs not being representative, differences between neighbouring GIs can sometimes only be revealed using interpolated data. Padthaway, Wrattonbully and Coonawarra are relatively small GIs that border one another. Only one climate station with >95% complete temperature data set for the 1971–2000 period is closest to all three GIs. Located in the NW corner of Wrattonbully, the Naracoorte climate station produced a GDD total of 1591°C-days. Any difference between the different GIs, which would be likely because of latitudinal variation, cannot be represented by a single station, yet the median GDD totals for Padthaway, Wrattonbully and Coonawarra from the interpolated climate data were 1657, 1554 and 1511°C-days, respectively. The third example is for the Yarra Valley GI, which contained no climate stations with a >95% record of temperature data for the 1971–2000 period. The Melbourne Airport climate station, which is located within the Sunbury GI, is likely to be the most representative of the Yarra Valley. Using this station to represent the Yarra Valley would not only lead to it being assigned the same GDD total as Sunbury, but also lead to information about the large range of GDDs from the interpolated data within the Yarra Valley not being conveyed. The varying topography of the Yarra Valley GI (with elevation ranging from 251 to 1339 m asl) is the main contributing factor to the large range of GDD totals within its area (ranging from 623 to 1708°C-days).

The distribution of climate types according to Winkler's GDD classification is illustrated in Figure 5 for nine selected GIs. The Yarra Valley GI crosses four categories, but its climate is predominantly best described as Region II, with 53% of its area falling within this category. For each of the other eight GIs, the spatial variability in climate spans at least two climate categories. The topographically varied Hunter Valley has the most spatially varied climate of the nine GIs spanning a total of five categories, but is mostly Region IV (33%) and Region V (46%), indicating that it is predominantly a warm to very warm GI. The Margaret River and Barossa Valley GIs, on the other hand, mostly fall into a single category (Region III, 84% and 67%, respectively), indicating these regions have relatively spatially homogeneous climates. Figure 5 demonstrates the level of spatial variability in climate within different GIs can be significant, indicating single climate stations are likely to not fully represent the climate within a GI.

Although care is needed to select an appropriate point in the ranges of index values calculated for each GI to effectively compare temperature regimes across regions, differences between GIs may be assessed using any of the indices. There are, however, subtle differences between the indices with the degree of difference varying. The GST and the GDD indices are very similar. The coefficient of determination of the first-order linear model that describes the relationship between these two indices is close to unity. Therefore, there is effectively no difference between the two indices except in terms of their magnitudes. The Winkler index (GDD) may be useful for determining stages of annual phenological development at time steps within a season, but, in terms of describing a region's GST, the GST is a simpler index with few methodological issues that produces a similar comparative result when considering the conditions over the whole season (Jones 2006, Jones et al. 2010).

The coefficients of determination for the models describing the relationships of HI with GST and GDD ($R^2 \approx 0.91$) indicate a functional difference. The HI differs to GST and GDD because it uses an estimate of the daytime temperature instead of mean diurnal temperature, includes a latitudinal day-length correction (K), and employs a slightly different period. The model that describes the relationship is again a first-order polynomial so there is a constant underlying rate of change in HI with

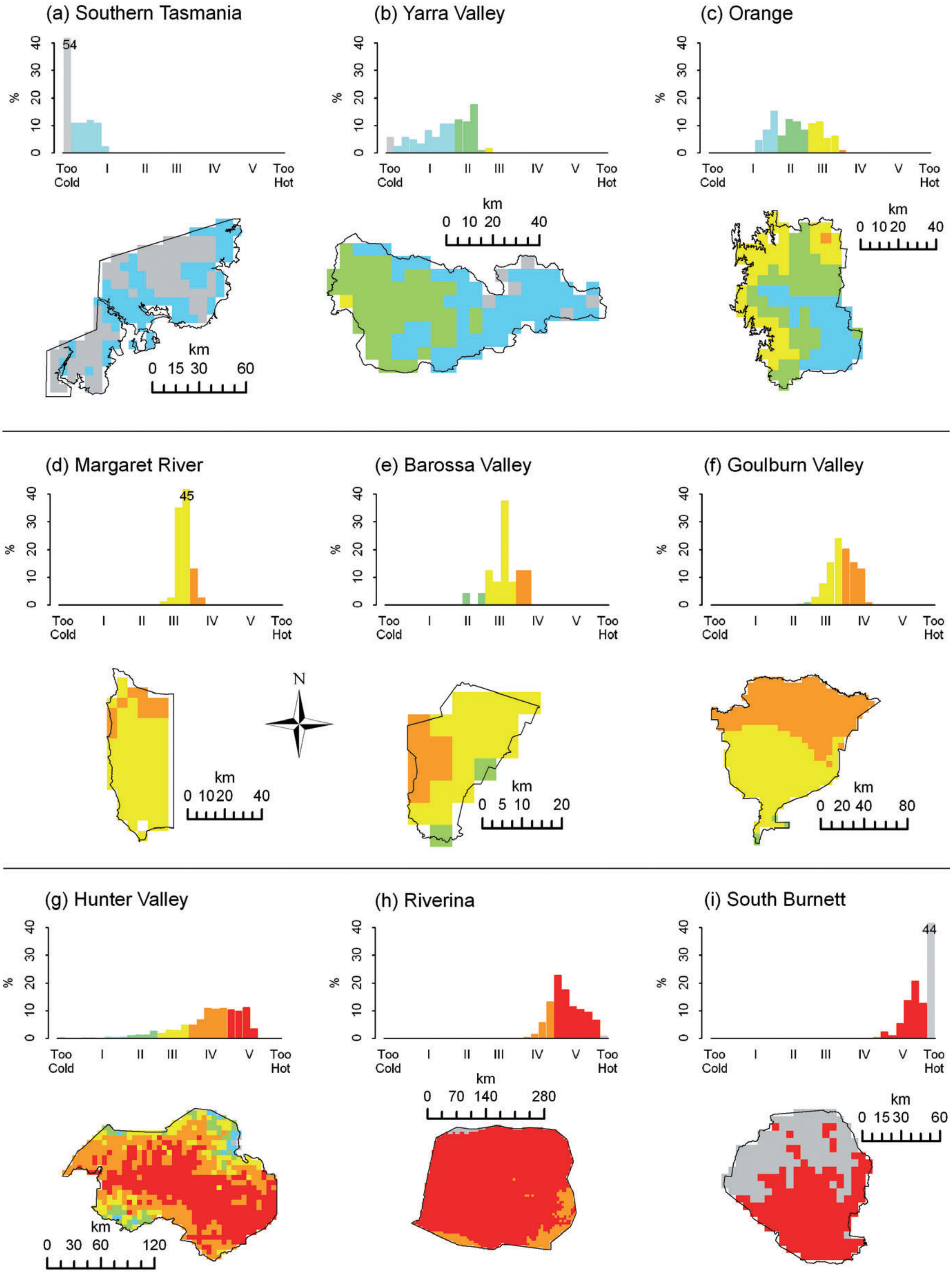

Figure 5. Distribution of climate types within nine selected geographical indications (GIs), categorised by Winkler's growing degree-day derived classes, shown as both histograms (with bars at 69.5°Cday intervals, approx. 1 quarter the range between the original Winkler categories) and maps (each pixel in the maps is a 0.05 decimal degree square). Histogram bars are restricted to 40% in the chart; those that extend beyond 40% are labelled with the actual percentage. Note: Southern Tasmania is not an officially established GI.

respect to either GST or GDD. The GIs with the largest residuals (i.e. the greatest difference between the modelled index and the actual index), Hastings River, Kangaroo Island and Shoalhaven, particularly demonstrate the differences caused by using daytime temperatures in the calculation. These three GIs have the least difference between their daytime temperatures and average diurnal temperatures because their humid coastal climates reduce diurnal temperature ranges.

The BEDD index is the most different to the other three indices. A second-order polynomial best describes the relationship between the BEDD and each of the other indices. The rate of increase in BEDD decreases as the other index values increase. In simple terms, at warmer temperatures, the rate of increase in BEDD is less than that of the other indices. The greatest cause of difference between the BEDD and the other indices, which produces the curvilinear relationship with the other indices, is an adjustment for vine temperature response. Gladstones (1992) cites various sources to derive that grapevine growth rates reach a maximum at 23–25°C, and bases a temperature response curve for grapevine growth on this temperature range. The response curve is approximated for in the calculation of the BEDD by capping degree-day accumulation to a maximum of 9°C-days per day. Gladstones (1992) assumes 'growth, as measured by plant weight, and rate of phenological development respond to temperature in much the same way', but cites no evidence for the phenological development rate following the plant-weight growth rate. The coefficients of determination for the models between BEDD and the other indices ($R^2 \approx 0.97$ for GDD and GST and $R^2 \approx 0.90$ for HI) suggest there are further differences than the slowing rate of increase in the index for warmer temperatures, caused by the adjustments for latitude and diurnal temperature range. The greatest residuals are for the most southerly and northerly GIs, North and South Tasmania and South Burnett, indicating latitude can have a greater effect on the BEDD than on the other indices.

The climates of the Australian GIs are compared against the climates of the American Viticultural Areas (AVAs) of the western United States (Figure 6) in Table 5 and Figure 7 using the GDD (Winkler) index. AVA boundaries in the western United States were created from the federally approved descriptions (Code of Federal Regulations, United States Federal Government 2008), resulting in a total of 131 polygons representing AVAs in California (109), Oregon (16, three shared with Washington and one with Idaho), Washington (9, three shared with Oregon), and Idaho (1, shared with Oregon) (Figure 6). The base temperature grids used to characterise the wine regions in the western United States were the official spatial climate data set of the United States Department of Agriculture, Parameter-elevation Regressions on Independent Slopes Model climate mapping system (PRISM, Daly et al. 2008).

Table 5 lists all AVA and GI regions by median GDD, showing that the Australian GIs are distributed throughout the list but with fewer regions in the cooler classifications. Only six Australian regions, Northern and Southern Tasmania (which are not officially established GIs), Macedon Ranges, Yarra Valley and Henty, fall within the Winkler I classification (or below in the case of Southern Tasmania). Figure 7 provides a fuller indication of the distribution of each of the two sets of regions. The full spatial range and inter-quartile range of GDD totals within each region are also conveyed in Figure 7, indicating that there is much overlap in terms of climate suitability for particular cultivars across the different regions. Examples of comparable Australian GIs and western United States AVAs on the median Winkler index values include: Region I – Southern Tasmania with Puget Sound and numerous Willamette Valley sub-AVAs; Region II – Coonawarra with Red Mountain, Upper Goulburn with the Sonoma Coast; Region III – Bendigo with Alexander Valley and the Dry Creek Valley, Margaret River with the Napa Valley; Region IV – Adelaide Plains with Lodi; and Region V – Swan District with Madera.

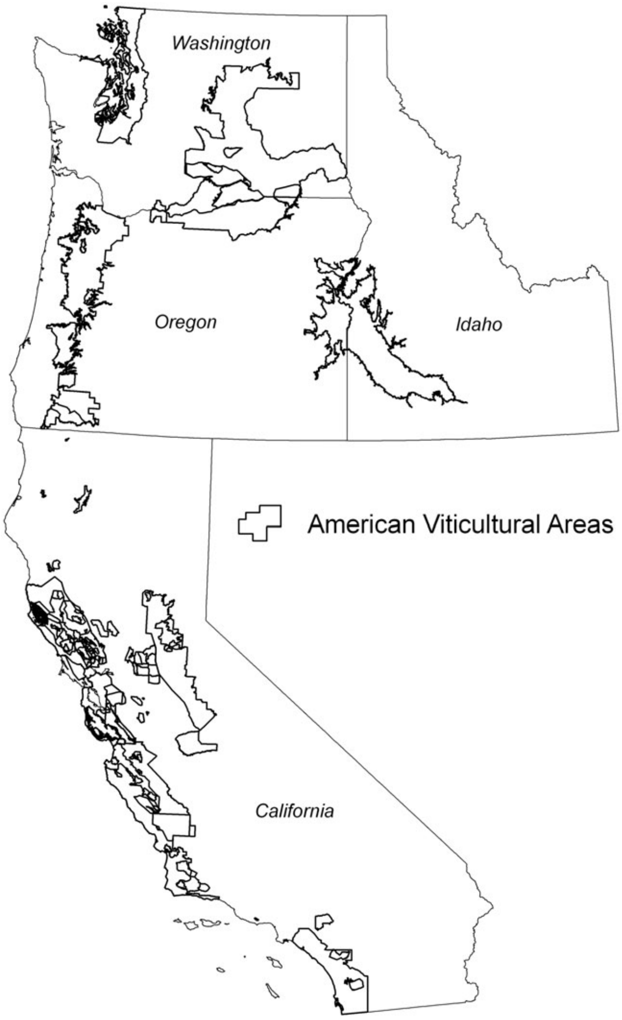

Figure 6. American viticultural areas of the western United States (Code of Federal Regulations, United States Federal Government 2008; figure from Jones et al. 2010).

Conclusions

Temperature indices provide key information for comparing wine region climates, yet, until now, no consistent set of indices has been available to enable direct comparisons

Table 5. AVAs of the western United States and GIs of Australia ordered by median GDD total.

Rank	Zone	Region name	Median GDD	Class	Rank	Zone	Region name	Median GDD	Class
1	GI	South Burnett	2673	V	100	GI	Manjimup	1721	III
2	AVA	Madera	2511	V	101	AVA	Cole Ranch	1714	III
3	GI	Swan District	2501	V	102	AVA	Potter Valley	1709	III
4	GI	Murray Darling	2416	V	103	GI	Heathcote	1709	III
5	AVA	Salado Creek	2386	V	104	AVA	Rockpile	1708	III
6	GI	Riverina	2380	V	105	AVA	Santa Clara Valley	1705	III
7	AVA	Cucamonga Valley	2368	V	106	GI	Great Southern	1705	III
8	AVA	Dunnigan Hills	2343	V	107	AVA	Chalone	1701	III
9	GI	Perth Hills	2341	V	108	AVA	Redwood Valley	1686	III
10	GI	Hastings River	2312	V	109	AVA	Covelo	1678	III
11	GI	Riverland	2305	V	110	AVA	Central Coast	1677	III
12	AVA	River Junction	2282	V	111	AVA	Sonoma Valley	1676	III
13	AVA	Temecula Valley	2264	V	112	AVA	Howell Mountain	1675	III
14	AVA	San Pasqual Valley	2239	V	113	AVA	Northern Sonoma	1668	III
15	GI	Swan Hill	2238	V	114	GI	Padthaway	1657	II
16	AVA	Borden Ranch	2224	V	115	GI	New England	1650	II
17	AVA	Saddle Rock-Malibu	2223	V	116	AVA	Dos Rios	1646	II
18	AVA	Sloughhouse	2222	V	117	AVA	Paicines	1643	II
19	GI	Cowra	2222	V	118	AVA	Los Carneros	1637	II
20	AVA	Clements Hills	2218	IV	119	AVA	Chalk Hill	1634	II
21	AVA	Lodi	2211	IV	120	AVA	North Coast	1632	II
22	GI	Adelaide Plains	2209	IV	121	AVA	San Benito	1612	II
23	AVA	Alta Mesa	2204	IV	122	GI	Eden Valley	1611	II
24	GI	Hunter Valley	2194	IV	123	AVA	San Francisco Bay	1608	II
25	AVA	Merritt Island	2184	IV	124	AVA	Yorkville Highlands	1601	II
26	AVA	Tracy Hills	2184	IV	125	GI	Pyrenees	1591	II
27	AVA	Cosumnes River	2178	IV	126	AVA	Bennett Valley	1589	II
28	AVA	Clarksburg	2176	IV	127	GI	Canberra District	1581	II
29	AVA	Jahant	2169	IV	128	AVA	Santa Ynez Valley	1580	II
30	AVA	Mokelumne River	2156	IV	129	GI	Southern Fleurieu	1580	II
31	AVA	Malibu-Newton Canyon	2152	IV	130	GI	Beechworth	1574	II
32	AVA	Capay Valley	2148	IV	131	AVA	Ben Lomond Mt.	1571	II
33	GI	Southern Flinders Ranges	2133	IV	132	GI	Wrattonbully	1554	II
34	AVA	Diablo Grande	2128	IV	133	AVA	Santa Cruz Mountains	1553	II
35	AVA	Sierra Foothills	2098	IV	134	GI	Southern Highlands	1552	II
36	GI	Peel	2091	IV	135	GI	Sunbury	1552	II
37	AVA	Solano Co Green Valley	2081	IV	136	GI	Kangaroo Island	1551	II
38	AVA	South Coast	2069	IV	137	GI	Orange	1551	II
39	AVA	Ramona Valley	2062	IV	138	AVA	Wahluke Slope	1545	II
40	GI	Gundagai	2020	IV	139	AVA	Walla Walla Valley WA†	1539	II
41	AVA	Hames Valley	2018	IV	140	AVA	Anderson Valley	1533	II
42	AVA	Wild Horse Valley	2017	IV	141	GI	Adelaide Hills	1530	II
43	AVA	Susiun Valley	2014	IV	142	AVA	Russian River Valley	1520	II
44	GI	Perricoota	2011	IV	143	AVA	Santa Maria Valley	1518	II
45	AVA	Shenandoah Valley	2009	IV	144	AVA	Walla Walla Valley OR†	1517	II
46	GI	Geographe	2008	IV	145	AVA	Lime Kiln Valley	1515	II
47	GI	Shoalhaven Coast	2006	IV	146	GI	Mornington Peninsula	1514	II
48	AVA	Red Hills Lake County	1998	IV	147	GI	Mount Benson	1512	II
49	GI	Rutherglen	1991	IV	148	GI	Coonawarra	1511	II
50	AVA	North Yuba	1980	IV	149	AVA	Red Mountain	1505	II
51	AVA	High Valley	1971	IV	150	AVA	Mendocino Ridge	1501	II
52	GI	Mudgee	1971	IV	151	AVA	Santa Rita Hills	1496	II
53	AVA	Stags Leap District	1962	IV	152	AVA	Sonoma Co Green Valley	1496	II
54	AVA	Fiddletown	1942	III	153	GI	Tumbarumba	1496	II
55	GI	Goulburn Valley	1942	III	154	AVA	Mount Harlan	1493	II
56	GI	Hilltops	1942	III	155	AVA	Arroyo Seco	1489	II
57	AVA	San Lucas	1939	III	156	AVA	Horse Heaven Hills	1476	II
58	GI	Glenrowan	1937	III	157	GI	Alpine Valleys	1476	II
59	AVA	Guenoc Valley	1934	III	158	GI	Robe	1474	II
60	AVA	Oakville	1908	III	159	AVA	Cienega Valley	1471	II
61	AVA	Paso Robles	1903	III	160	GI	Geelong	1466	II
62	AVA	Calistoga	1901	III	161	GI	Strathbogie Ranges	1452	II
63	AVA	Fair Play	1901	III	162	GI	Upper Goulburn	1451	II
64	AVA	San Antonio Valley	1900	III	163	AVA	Sonoma Coast	1442	II

Table 5. *Continued*

Rank	Zone	Region name	Median GDD	Class	Rank	Zone	Region name	Median GDD	Class
65	AVA	Yountville	1898	III	164	AVA	Monterey	1441	II
66	AVA	El Dorado	1898	III	165	AVA	Santa Lucia Highlands	1440	II
67	AVA	St. Helena	1896	III	166	AVA	Yakima Valley	1425	II
68	AVA	Rutherford	1895	III	167	AVA	Seiad Valley	1413	II
69	GI	Langhorne Creek	1894	III	168	GI	Grampians	1408	II
70	GI	Margaret River	1887	III	169	AVA	Carmel Valley	1392	II
71	AVA	Napa Valley	1883	III	170	AVA	Trinty Lakes	1390	II
72	AVA	Mt. Veeder	1872	III	171	AVA	Snake River Valley ID†	1386	I
73	AVA	Tulocay	1867	III	172	AVA	York Mountain	1369	I
74	GI	McLaren Vale	1865	III	173	AVA	Arroyo Grande Valley	1366	I
75	AVA	Diamond Mountain	1857	III	174	GI	Henty	1354	I
76	GI	Barossa Valley	1852	III	175	AVA	Columbia Valley OR†	1344	I
77	AVA	San Ysidro District	1849	III	176	GI	Yarra Valley	1343	I
78	GI	Clare Valley	1847	III	177	AVA	Columbia Valley WA†	1314	I
79	AVA	Chiles Valley	1840	III	178	AVA	Edna Valley	1302	I
80	GI	Granite Belt	1821	III	179	AVA	Snake River Valley OR†	1272	I
81	GI	Blackwood Valley	1819	III	180	AVA	Rogue Valley	1225	I
82	AVA	Clear Lake	1815	III	181	GI	Macedon Ranges	1217	I
83	AVA	Oak Knoll District	1807	III	182	AVA	Rattlesnake Hills	1205	I
84	AVA	Benmore Valley	1805	III	183	AVA	Applegate Valley	1195	I
85	AVA	Sonoma Mountain	1803	III	184	AVA	Southern Oregon	1165	I
86	AVA	McDowell Valley	1802	III	185	AVA	Umpqua Valley	1115	I
87	GI	Currency Creek	1795	III	186	AVA	Willamette Valley	1081	I
88	AVA	Knights Valley	1788	III	187	AVA	Dundee Hills	1081	I
89	AVA	Spring Mountain District	1785	III	188	AVA	Ribbon Ridge	1073	I
90	AVA	Pacheco Pass	1774	III	189	AVA	Yamhill-Carlton District	1072	I
91	AVA	Mendocino	1774	III	190	AVA	McMinnville	1066	I
92	AVA	Livermore Valley	1774	III	191	AVA	Eola-Amity Hills	1059	I
93	AVA	Willow Creek	1753	III	192	AVA	Chehalem Mountains	1047	I
94	GI	Bendigo	1746	III	193	GI	Northern Tasmania‡	1034	I
95	AVA	Alexander Valley	1741	III	194	AVA	Red Hills of Douglas County	1019	I
96	AVA	Dry Creek Valley	1724	III	195	AVA	Columbia River Gorge OR†	925	I
97	AVA	San Bernabe	1723	III	196	AVA	Columbia River Gorge WA†	881	I
98	GI	Pemberton	1722	III	197	AVA	Puget Sound	851	I
99	AVA	Atlas Peak	1721	III	198	GI	Southern Tasmania‡	837	N/A

Class refers to Winkler region classification. Rank is from warmest total GDD to coolest and refers to labels in Figure 7. †Each of these AVAs spans two states and has been split for differentiation by state. ‡Tasmanian regions are not officially established GIs. GI, geographical indication; AVA, American viticultural areas; GDD, growing degree-days.

between countries. In addition, historical comparisons of the climate characteristics between regions have been done using individual stations, which can vastly under or overestimate the true climate structure in a given wine region. The data and methodology presented in this paper contribute a set of climate indices and their spatial characteristics for Australia's winegrape-growing regions. The results show that spatial variability of the climate indices within regions can be significant; and that understanding their distribution provides a measure of understanding the range of cultivar suitability within wine regions.

Functional differences between the selected temperature indices were identified. Season total GDD was nearly functionally identical to GST, as both indices were calculated using average daily temperature data only. The HI was functionally similar to GST and GDD, but varied for some regions because it uses an estimate of daytime temperature (instead of average diurnal temperature) and includes a modification to account for day-length, which varies by latitude. BEDD totals were the most different to the other indices because of the cap placed on the number of degree-day units that can be accumulated on any one day. This resulted in the rate of increase in the BEDD with respect to increases in the other indices slowing at higher temperatures. A consequence of the dissimilarity among the indices is that descriptions of temperature regime differences between the same region pairs can vary depending upon which index is employed.

In selecting an index most suitable for indicating economically sustainable winegrape production, there appears to be no advantage in using the indices with more complex formulas than simple average GST. Capping the

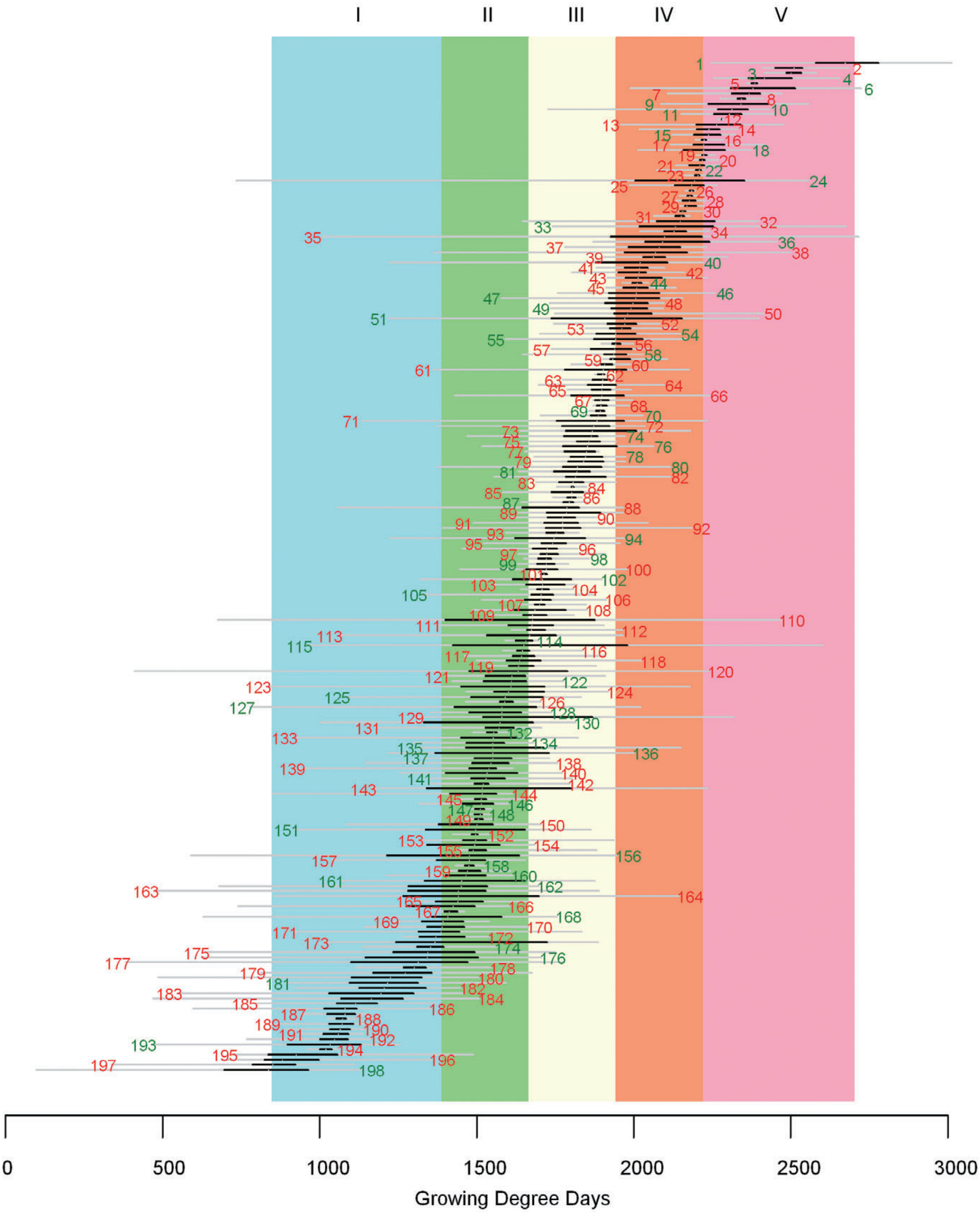

Figure 7. Summary chart of growing degree-days (GDD) totals for all Australian geographical indications (GIs) and American viticultural areas (AVAs) of the western United States. Grey bars represent full range of GDD totals, black bars represent the inter-quartile range, and white points represent the median. Number labels represent each region ID as in Table 5. Green numbers are Australian GIs. Red numbers are AVAs.

heat accumulation component of the BEDD index to 9°C, renders the BEDD insensitive to increasing temperatures in already warm regions and would therefore be the least suitable for climate change modelling. Latitude adjustments incorporated within both the HI and the BEDD are, however, likely to be valuable at providing values closer to the actual daily mean temperature, and therefore, more representative of a region's viticultural suitability. The HI does not include a cap on heat accumulation but does include a latitude adjustment factor so it is perhaps the most suitable of the four indices for viticultural climate change impact studies. The HI does not include the seventh warmest month (April/October in the Southern/Northern Hemisphere), which is of value when determining limits of production in cool regions. Perhaps the best solution would be an index with the basic simplicity of the GST (of the seven warmest months), but modified for latitude, achieved by simply multiplying the GST by K (Eqns 1–4). To more fully describe the potential suitability of a climate type for long-term commercially successful winegrape production, accompanying indices that describe spring frosts and extreme heat could also be determined, such as the temperature variability index, spring frost index or heat stressfulness index (see Gladstones 1992, 2004).

While each of the temperature indices examined in this research have been developed with viticultural suitability in mind (Winkler et al. 1974, Huglin 1978, Gladstones 1992, Jones 2006), their applicability to other wine regions from where they were developed has not been fully examined. The data and methods presented here and by others (Jones et al. 2009, 2010) are providing a more holistic look at climate index characteristics globally and the framework by which regional validation can be examined. Furthermore, it is important that ongoing updates to the spatial characterization of the indices be completed as data becomes available, i.e. more recent data (e.g. 1981–2010) and at a higher spatial resolution, so as to keep these index values up-to-date in a changing climate and at an increasing level of accuracy and precision.

Acknowledgements

This work is supported by the Wine Growing Futures Program through the Grape and Wine Research and Development Corporation of the Australian Federal Government, the National Wine & Grape Industry Centre, and by a Charles Sturt University Competitive Grant. The authors appreciate the ongoing support provided by the Charles Sturt University Spatial Analysis Network (CSU-SPAN).

References

Australian Wine and Brandy Corporation (2008) Australian geographical indications: regions [electronic resource] (Australian Wine and Brandy Corporation: Adelaide).

Bureau of Meteorology (2010) Australian water availability – temperature archive. http://www.bom.gov.au/jsp/awap/temp/archive.jsp [accessed 24/2/10].

Daly, C., Halbleib, M., Smith, J.I., Gibson, W.P., Doggett, M.K., Taylor, G.H., Curtis, J. and Pasteris, P.A. (2008) Physiographically-sensitive mapping of temperature and precipitation across the conterminous United States. International Journal of Climatology **28**, 2031–2064.

Donn, W.L. (1975) Meteorology (McGraw-Hill: New York).

Gladstones, J. (1992) Viticulture and environment (Winetitles: Adelaide).

Gladstones, J.S. (2004) Climate and Australian viticulture. In: Viticulture volume 1 – resources. Eds. P.R. Dry and B.G. Coombe (Winetitles: Adelaide) pp. 90–118.

Glarner, H. (2006) Length of day and twilight (formulas). http://www.gandraxa.com/length_of_day.aspx [accessed 28/7/09].

Huglin, P. (1978) Nouveau mode d'évaluation des possibilités héliothermiques d'un milieu viticole. Comptes rendus de l'académie d'agriculture de France **64**, 1117–1126.

Huglin, P. and Schneider, C. (1998) Biologie et écologie de la vigne (Lavoisier: Paris).

Intergovernmental Panel on Climate Change (IPCC) (2007) Summary for policymakers. In: Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Eds. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (Cambridge University Press: Cambridge and New York) pp. 1–18.

Jet Propulsion Laboratory (2004) Seamless Shuttle Radar Topography Mission (SRTM) 3 arc second version 2. http://dds.cr.usgs.gov/srtm/version2_1/SRTM3/Australia/ [accessed 18/3/06].

Jones, G.V. (2006) Climate and terroir: impacts of climate variability and change on wine. In: Fine wine and terroir – the geoscience perspective. Eds. R.W. Macqueen and L.D. Meinert (Geological Association of Canada: St. John's) pp. 203–216.

Jones, G.V., Moriondo, M., Bois, B., Hall, A. and Duff, A. (2009) Analysis of the spatial climate structure in viticulture regions worldwide. Le Bulletin de l'Organisation Internationale de la Vigne et du Vin **82**, 507–518.

Jones, G.V., Duff, A., Hall, A. and Myers, J. (2010) Spatial analysis of climate in winegrape growing regions in the western United States. American Journal of Enology and Viticulture **61**, 313–326.

McIntyre, G.N., Kliewer, W.M. and Lider, L.A. (1987) Some limitations of the degree-day system as used in viticulture in California. American Journal of Enology and Viticulture **38**, 128–132.

Sturman, A.P. and Tapper, N.J. (1996) The weather and climate of Australia and New Zealand (Oxford University Press: Melbourne, Oxford, Auckland, New York).

United States Federal Government (2008) Code of Federal Regulations: alcohol, tobacco products, and firearms (title 27, parts 1–199). In: Part 9 – American viticultural areas. (Alcohol and Tobacco Tax and Trade Bureau, Department of the Treasury, U.S. Government: Washington, DC) pp. 101–223.

Went, F.W. (1957) Experimental control of plant growth (Chronica Botanica Co.: Walthan).

Winkler, A.J., Cook, J.A., Kliewer, W.M. and Lider, L.A. (1974) General viticulture (University of California Press: Berkeley, Los Angeles, London).

Manuscript received: 7 December 2009
Revised manuscript received: 19 April 2010
Accepted: 23 April 2010