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ORIGINAL RESEARCH ARTICLE

Climate trends and variability in the Chilean viticultural production zones during 1985–2015

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ABSTRACT

Chile is characterised by offering high-quality wine and table grapes and its renowned viticultural valleys. Chile has been considered vulnerable to climate change, bringing a major concern to the national wine sector. This research aimed to analyse the climate trends and variability of Chilean viticulture from 1985 to 2015, evaluating meteorological, bioclimatic and risk indices at forty-seven weather stations. Meteorological data indicated that the warmest zone was Atacama, while the coldest was Aysén. The rainiest region was Austral, while the driest was Arica and Parinacota. Growing-season indices (GST, GDD and HI) showed that Central Valley was warmer than Arica and Parinacota, whereas the latter presented a higher sum of spring temperatures (SONMean and SONMax). Atacama presented the highest risk for T > 30 °C, whereas Central and South Valleys for T > 35 °C. The highest frost risk was in Aysén, while the lowest was in Arica and Parinacota. Tmin decreased by 0.33 ºC, while Tmax increased by 0.83 ºC. None of the trends for precipitation (PP) were statistically significant. GST, GDD, HI, BEDD, SONMean and SONMax increased by 0.58 ºC, 118.29 heat units, 140.57 heat units, 79.72 heat units, 8.42 heat units and 45.17 heat units, respectively, while CI decreased by 0.19 ºC. Some stations with negative trends for CI also coincided with the highest Tmax. Locations in Coquimbo and Aconcagua valleys changed from intermediate to warm climates. Locations from Coquimbo and Central valleys changed from warm to hot climates. Quilaco changed from a cool to a warm climate, while Osorno changed from without classification to a cool climate. PCA analysis reported that meteorological variables were related to the distance of the site to the Pacific Ocean. This information is important for the national industry and may allow producers to define mitigation strategies for climate change.

KEYWORDS: bioclimatic indices, climatic variability, global warming, grape, risk indices, viticulture

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INTRODUCTION

Chilean viticulture is mostly characterised by its Mediterranean climates and is renowned for wines, Pisco, table grapes and raisins of high quality. Currently, Chile is the fourth-largest exporter of wines worldwide and the largest exporter of table grapes in terms of volume (OIV, 2018). Thus, considering the importance of vine production for Chile, the effect of climate change on viticulture is a significant issue, even more so considering that the country is under severe ongoing drought (Garreaud *et al*., 2020).

Climate change has affected vine physiology, berry quality and grapevine variety distribution in different wine-growing regions (Jones *et al*., 2005; Salazar-Parra *et al*., 2010; Salazar-Parra *et al*., 2012; Gutiérrez-Gamboa *et al*., 2021). Bioclimatic indices suggest climate change will negatively affect vine cultivation in Southern Europe, while in Central and Western Europe, it could benefit wine quality and open new areas for viticulture (Malheiro *et al*., 2010; Droulia and Charalampopoulos, 2021). Similar effects are observed in Chile, in which vineyard plantations are moving to the southern areas. An example is that the vineyard surface in La Araucanía Region (38º44’ S) increased by 953 % from 2003–2020. Vines are also being cultivated in Los Ríos (39º49’ S) and in Los Lagos (41º28’ S) regions.

Chile is considered vulnerable to climate change (CEPAL, 2012). Thus, environmental changes due to climate change are of major concern to vine producers, wineries, exporters, and researchers. Chilean grape and wine production have developed in different valleys, characterised by specific climatic conditions, from the Arica and Parinacota Region (18º49’ S) to Los Lagos Region (41º28’ S). The Decree Nº464 of the Chilean Ministry of Agriculture (2012) established six viticulture zones; Atacama, Coquimbo, Aconcagua, Central Valley, South and Austral, which are divided in sub valleys (Figure 1, Table 1) that provide specific characteristics to grape and wine production. However, due to the current climatic scenario, Chilean winemakers have found new viticulture areas to produce differentiated wines with respect to those made in the most famous national areas. Considering the current climatic scenario, it is important to study the areas of the southern region complemented with areas located in the extreme south of Chile, such as Chile chico in Aysén, where one of the southernmost wines in the world is produced (Arribillaga and Reyes, 2021).

To characterise the climate of a viticultural region, OIV (2015) proposes to evaluate long-term time series with a minimum of 30 years of climatic variables (average, minimum and maximum temperatures, precipitation, cold hours, evapotranspiration, among other variables), bioclimatic indices [Huglin Heliothermal Index (HI), Growing Degree Days (GDD), Biologically Effective Degree Days (BEDD), Growing Season Temperature (GST) and Cold Night Index (CI)], and risk indices, such as frost days (number of days in which temperature is lower than 0 °C) and maximum temperatures (number of days in which temperature is higher than 30 and 35 °C). Based on this, previous reports have evaluated the evolution of climate in viticulture, providing adaptation guidelines to future changes in the climate (Jones and Davis, 2000; Tonietto and Carbonneau, 2004; Petrie and Sadras, 2008; Schwarz *et al*., 2010; Montes *et al*., 2012; Lereboullet *et al*., 2014; Deis *et al*., 2015; Jarvis *et al*., 2017; Jones, 2018; Cogato *et al*., 2019). In this fashion, Tonnieto and Carbonneau (2004) proposed a multicriteria climate classification (MCC), using three bioclimatic indices (HI, CI, and aridity index) for describing on a macro climatic scale, the viticultural regions, and relate them to different variables. These indices were also used in some studies to characterise different viticultural climatic zones in Chile (Montes *et al*., 2012; Gutiérrez-Gamboa *et al*., 2018; Verdugo-Vásquez *et al*., 2021). Recently, Jarvis *et al*. (2017)

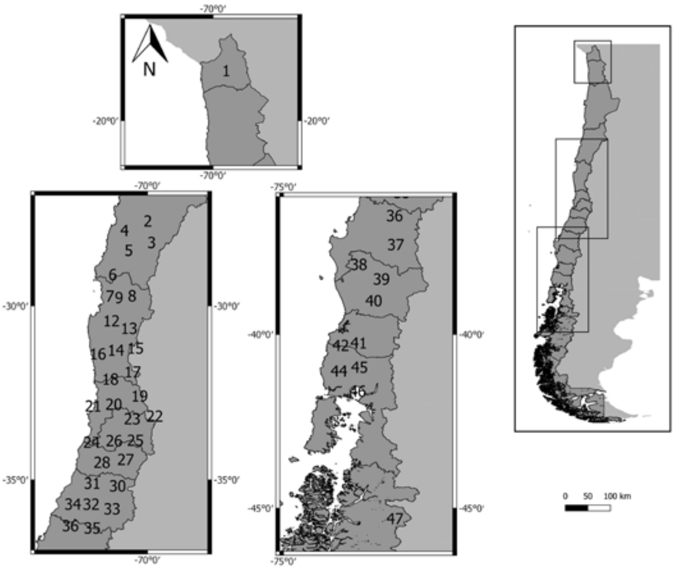

FIGURE 1. Spatial distribution of the weather stations. More information about the weather stations is available in Table 1 and Supplementary Table 1.

TABLE 1. Location and data available of the weather stations used in the study.

Administrative region	Viticulture region*	Valley*	Weather station name	Map number**	Years of data available (1985–2015 period)
Arica and Parinacota	Arica and Parinacota	-	Codpa	1	28
Atacama	Atacama	Copiapó	Los Loros	2	26
			Lautaro Embalse	3	29
		Huasco	Canto de Agua	4	27
			Santa Juana	5	30
Coquimbo	Coquimbo	Elqui	El Trapiche	6	30
			La Florida	7	31
			Rivadavia	8	31
			Vicuña	9	29
			La Ortiga	10	31
		Limarí	Hurtado	11	26
			Paloma Embalse	12	31
			Caren	13	27
			Cogotí Embalse	14	31
			Las Ramadas	15	31
		Choapa	Illapel	16	30
			La Tranquilla	17	30
			Los Cóndores	18	28
Valparaíso	Aconcagua	Aconcagua	Vilcuya	19	28
		Marga-Marga	Lliu-Lliu Embalse	20	29
		Casa Blanca	Lago Peñuelas	21	30
		San Antonio	Santo Domingo	24	31
Metropolitana	Central Valley	Maipo	Los Panguiles	22	31
			Quinta Normal	23	31
			Pirque	25	28
			Melipilla	26	24
O'Higgins		Rapel	Rengo	27	22
			Convento Viejo	28	23
Maule		Curicó	General Freire	29	31
			Potrero Grande	30	29
		Maule	Pencahue	31	29
			Talca UC	32	31
			Colorado	33	29
			Cauquenes	34	29
			Parral	35	30
Ñuble	South	Itata	Bernardo O'Higgins	36	31
Bio-Bio		Bío-Bío	Quilaco	37	29
Araucanía		Malleco	Traiguén	38	26
	Austral	Cautín	Carillanca	39	28
			Maquehue	40	30
Los Lagos		Osorno	Remehue	41	28
			Adolfo Matthei	42	31
			Canal Bajo	43	30
			La Pampa	44	24
	-	-	Frutillar	45	25
	-	-	El Tepual	46	31
Aysén	Aysén	-	Coyhaique	47	25

*According to Decree N°464 of Chile. **Map numbers refer to the numbers in the Map in Figure 1 - Undefined.

proposed two new bioclimatic indices, the Mean Spring Temperature Summation (SONMean) and the Maximum Spring Temperature Summation (SONMax). These indices show a higher correlation with harvest dates in Australian vineyards than the other bioclimatic indices calculated (Jarvis *et al*., 2017).

Based on this, it is important to study the changes in the climate in the different Chilean viticultural zones to improve production and competitiveness and to perform mitigation strategies to face climate change. Therefore, the main aim of this research was to analyse the climate trends and variability of the Chilean viticulture production zones over three decades (from 1985 until 2015), with an emphasis on meteorological, bioclimatic and risk indices. This is the first study that analyses the trend and variability of the climate in Chile in viticultural zones from north and south, considering data from 47 weather stations.

MATERIALS AND METHODS

1. Climate data and weather station selection

Climate variables such as precipitation and maximum and minimum temperature data were extracted from 47 weather stations located across the main Chilean wine-growing zones from Codpa to Coyhaique. These weather stations are distributed from 18.8º S to 45.6º S latitude, from 69.7º W to 73.2º W longitude, and from 55 to 1870 elevation (m), covering the main viticulture and potential zones of Chile (Figure 1 and Table 1). The vineyards distributed in this macrozone are mainly grown under drip irrigation and are trained to vertical shoot-positioning systems (Montes *et al*., 2012). The “Dirección General de Aguas (DGA), “Dirección Meteorológica de Chile” (DMC) and “Instituto de Investigaciones Agropecuarias” (INIA) are the administers of the weather stations.

The selection of weather stations was based on two criteria: (i) the station should well represent a viticultural production area or a potential productive zone under climate change conditions, and (ii) it should have at least 22 years of temperature and precipitation records between 1985 to 2015. Thus, the average number of years with data from all weather stations was 28.7 years (Table 1). This climate database represents the greatest diversity of the wine-growing regions of Chile with the widest range of data available. The geographical information of the 47 selected weather stations is shown in Supplementary Table 1.

2. Gap filling

To avoid mistakes due to gaps in the data, climate records were filled in when the gap length was less than three consecutive days. In this way, when the gap was one day, data were filled using an average of the day before and the following day. In addition, when the gap was two days, data were filled, duplicating the last record before the gap and the following gap records, respectively. Lastly, when the gap was three days, data were filled, duplicating the last record before the gap for the first missing datum, duplicating the following records to the gap for the last missing datum, and using the average between both dates for the central missing date (Pappas *et al*., 2014). This process was applied only for temperature data, not for rainfall, as it was only considered for whole seasons.

3. Climatic indices

Based on climate data, three classes of indices were calculated: a) meteorological indices, which summarise minimum and maximum temperatures and precipitation conditions, b) bioclimatic indices, which summarise climate conditions with biological relevance to vine growing and c) risk indices, which summarise temperature events that could injure leaves, flowers, or fruit, such as frost or extreme heat. More information about the calculated indices and their references are presented in Table 2.

4. Statistical analysis

To characterise the average and variability of the indices, the mean and the coefficient of variation (CV, %) were calculated for each weather station and climatic index. In addition, in regions with more than one station, the data were averaged to obtain values summarised for each region.

To characterise the trends and significance of each index, a non-parametric Mann–Kendall test (Mann, 1945; Kendall, 1975) and Sen’s slope estimator (Sen, 1968) were used. The Mann–Kendall test indicates whether a trend presented statistical significance with a confidence level of 95 % (p-value < 0.05). Sen’s slope estimator provides information about the magnitude of a downward or upward trend in the period under study, expressed as a change per year. Both tests are less affected by extreme values and do not require normal distribution.

Principal Component Analysis (PCA) was performed with the aim to find relationships between mean, trends (unit/year) and variability (CV, %) of the different calculated indices and geographic variables of the weather station (latitude, longitude, elevation and distance to the Pacific Ocean). PCA is a descriptive data analysis tool used to describe a data set in terms of new uncorrelated variables (“components”). In this study, PCA allows for visualising the correlations between variables (calculated indices and geographic variables of the weather station). The XLSTAT software, version 2020.3.1 (Addinsoft SARL, Paris, France), was used to perform all the analysis.

RESULTS

1. Mean value of the indices

1.1. Meteorological indices

Table 3 shows the descriptive analysis obtained for the different calculated indices, considering the eight viticulture regions (Table 1), from the 1985–2015 period. The descriptive analysis for each of the 47 weather stations is presented in Supplementary Tables 2 (meteorological and risk indices) and 3 (bioclimatic indices). The mean value

TABLE 2. Climatic indices used, equations, calculation period and reference.

Index Type	Index name	Equation	Period	Reference
Meteorological	Minimum Temperature (Tmin, °C)	$Tmin = \frac{\sum_{d=1}^{n} T\ Min}{n}$	01 January to 31 December	OIV (2015)
	Maximum Temperature (Tmax, °C)	$Tmax = \frac{\sum_{d=1}^{n} T\ Max}{n}$		
	Precipitation (PP, mm)	$PP = \frac{\sum_{d=1}^{n} PP}{n}$		
Bioclimatic	Growing Season Temperature (GST, °C)	$GST = \frac{\sum_{d=1}^{n} \frac{T\ Max + T\ Min}{2}}{n}$	01 October to 30 April	Jones (2006)
	Growing Degree Days (GDD, heat units)	$GDD = \sum_{d=1}^{n} max \frac{(T\ Max + T\ Min)}{2} - 10$	01 October to 30 April	Amerin and Winkler (1944)
	Huglin Heliothermal (HI, heat units)	$HI = \sum_{d=1}^{n} max \left(\frac{(T\ Mean - 10 + T\ Max - 10)}{2} \right) k$	01 October to 31 March	Huglin (1978)
	Biologically effective growing degree days (BEDD, heat units)	$BEDD = \sum_{d=1}^{n} min \left[max \left(\frac{T\ Max + T\ Min}{2} - 10 \right), 9 \right] TRadj.k$ $TRadj = \begin{Bmatrix} 0.25[TR - 13], [TR] > 13 \\ 0.0, \quad 10 < [TR] < 13 \\ 0.25[TR - 10], [TR] < 10 \end{Bmatrix}$	01 October to 30 April	Gladstones (1992)
	Cool Night (CI, °C)	$CI = \frac{\sum_{d=1}^{n} T\ Min}{n}$	01 March to 31 March	Tonietto (2004)
	Mean spring t emperature summation (SONMean, heat units)	$SONMean = \sum_{d=1}^{n} T\ mean$	01 September to 30 November	Jarvis *et al.* (2017)
	Maximum spring temperature summation (SONMax, heat units)	$SONMax = \sum_{d=1}^{n} T\ max$		
Risk	T > 30 °C (days)	$T > 30\ °C = \sum_{d=1}^{n} Number\ of\ day\ T\ Max > 30\ °C$	01 September to 01 May	
	T > 35 °C (days)	$T > 35\ °C = \sum_{d=1}^{n} Number\ of\ day\ T\ Max > 35\ °C$		
	T < 0 °C (days)	$T < 0\ °C = \sum_{d=1}^{n} Number\ of\ day\ T\ Min < 0\ °C$		

Where: T Min, daily minimum temperature (°C); T Max, daily maximum temperature (°C); T Mean, daily mean temperature [(T min+T max)/2] (°C); k is an adjustment for latitude/day length; n is the number of days in the period.

of minimum temperature (Tmin), maximum temperature (Tmax) and precipitation (PP) were 7.9 ºC, 21.4 ºC and 572.3 mm, respectively, while the standard deviations were 1.6 ºC, 3.5 ºC and 474.7 mm, respectively, across all eight viticulture regions (Table 3). The highest mean value of Tmax was observed in Lautaro Embalse (Atacama Region) (29 °C), and the lowest was observed in Coyhaique (Aysén Region) (13.2 °C), whereas the highest mean value of Tmin was observed in Embalse Cogotí (Coquimbo Region) (10.8 °C) and the lowest was observed in Coyhaique (3.9 °C). The highest mean precipitation was observed in El Tepual (Los Lagos Region) (1596.3 mm per year), and the lowest mean precipitation was observed in Codpa (Arica and Parinacota Region) (17.7 mm per year) (Supplementary Table 2). Based on the data, the warmest viticultural zone was Atacama, exhibiting mean values of Tmin and Tmax of 9.7 and 26.5 ºC, respectively, whereas the coldest zone was Aysén, with mean values of Tmin and Tmax of 3.9 and 13.2 ºC, respectively (Table 3). Based on the results, the wettest region was Austral (1284.1 mm), and the driest was Arica and Parinacota (17.7 mm) (Table 3).

1.2. Bioclimatic indices

The mean value for Growing Season Temperature (GST) was 17.0 ºC, with a standard deviation of 2.4 ºC. The mean value for Growing Degree Days (GDD) was 1507.8 heat units, with a standard deviation of 483 heat units. The mean value for Huglin Index (HI) was 2036.7 heat units, with a standard deviation of 507.9 heat units. The mean value for Biologically Effective Growing Degree Days (BEDD) was 1253.0 heat units, with a standard deviation of 333.4 heat units. The mean value for Cool Night Index (CI) was 10.0 ºC, with a standard deviation of 1.9 ºC. Mean values for Mean Spring Temperature Summation (SONMean) and Maximum Spring Temperature Summation (SONMax) were 1301.9 and 1928.4 heat units, respectively, whereas the standard deviations for both indices were 223.4 and 334.7 heat units, respectively (Table 3). The mean values of bioclimatic indices calculated

TABLE 3. Mean values of the indices for each viticulture region (Table 2) and descriptive statistics were obtained for the different indices, considering the 47 weather stations under study (mean 1985–2015 period).

Viticulture region	Meteorological			Bioclimatic							Risk		
	Tmin (ºC)	Tmax (ºC)	PP (mm)	GST (ºC)	GDD (h.u.)	HI (h.u.)	BEDD (h.u.)	CI (ºC)	SONmean (h.u.)	SONmax (h.u.)	T > 30 ºC (days)	T > 35 ºC (days)	T < 0 ºC (days)
Arica and Parinacota	7.1	24.7	17.7	16.7	1432.0	1873.1	1277.0	9.8	1420.9	2276.4	2.0	0.0	0.0
Atacama	9.7	26.5	38.6	19.8	2072.1	2560.1	1570.0	11.8	1625.4	2424.3	66.8	0.7	0.2
Coquimbo	9.5	23.7	152.3	18.7	1841.6	2296.0	1456.1	11.9	1477.0	2142.3	32.3	0.3	0.1
Aconcagua	7.9	20.6	481.4	16.5	1376.8	1856.9	1155.6	10.0	1256.0	1838.8	18.9	0.4	0.5
Central Valley	7.6	21.5	631.9	17.7	1643.7	2267.9	1387.2	9.8	1304.4	1944.9	42.2	1.5	1.8
South	6.7	19.4	1146.9	16.0	1282.7	1923.2	1165.3	8.6	1147.5	1733.3	25.2	1.6	4.1
Austral	6.0	16.5	1284.1	13.3	752.1	1271.0	723.1	7.5	981.0	1464.1	2.9	0.2	7.3
Aysén	3.9	13.2	895.6	11.4	467.1	915.0	467.0	6.4	793.7	1258.4	0.9	0.0	15.4
Minimum^x	3.9	13.2	17.7	11.4	434.9	860.2	409.5	6.4	793.7	1258.4	0.0	0.0	0.0
Maximum	10.8	29.0	1596.3	20.8	2296.4	2852.4	1628.4	13.7	1756.6	2678.1	139.9	10.8	15.4
1st quartile	6.6	18.7	149.2	15.7	1212.3	1632.3	1020.8	8.7	1157.4	1655.1	2.4	0.0	0.0
Median	7.8	21.6	444.5	17.9	1668.1	2223.7	1396.7	10.1	1337.4	1941.3	25.0	0.2	0.5
3rd quartile	9.0	24.1	998.7	18.7	1840.6	2400.4	1489.9	11.5	1466.3	2183.7	45.7	0.6	1.9
Mean	7.9	21.4	572.3	17.0	1507.8	2036.7	1253	10.0	1301.9	1928.4	30.0	0.7	2.4
Standard deviation	1.6	3.5	474.7	2.4	483.0	507.9	333.4	1.9	223.4	334.7	29.0	1.7	3.9

^{x} Statistic was computed used all the weather stations. h.u. = Heat units. Abbreviations according to Table 2. Colour degradation from light blue (lower values) to red (higher values), except for Precipitation (PP) and T < 0 °C, which is in the opposite direction.

for each weather station are shown in Supplementary Table 3. Lautaro Embalse (Atacama Region) presented the highest mean values of most of the calculated bioclimatic indices, with a GST (20.8 ºC), GDD (2296.4 heat units), HI (2852.4 heat units), BEDD (1628.4 heat units), SONMean (1756.6 heat units) and SONMax (2678.1 heat units), except for CI, where the maximum mean value was reached in Embalse Cogotí (Coquimbo Region) (13.7 ºC). The minimum mean values of GST, CI, SONMean and SONMax were observed in Coyhaique (Aysén Region), with 11.4 ºC, 6.4 ºC, 793.7 and 1258.4 heat units, respectively. Frutillar (Los Lagos Region) exhibited the lowest mean values of GDD (434.9 heat units), HI (860.2 heat units) and BEDD (409.5 heat units). Based on the results at the viticulture region level (Table 3), Atacama Region presented the highest mean values of GST (19.8 ºC), GDD (2072.1 heat units), HI (2560.1 heat units), BEDD (1570.0 heat units), SONMean (1625.4 heat units) and SONMax (2424.3 heat units), whereas Coquimbo Region reached the highest mean value of CI (11.9 ºC). Aysén Region presented the lowest mean values of GST (11.4 ºC), GDD (467.1 heat units), HI (915.0 heat units), BEDD (467.0 heat units), CI (6.4 ºC), SONMean (793.7 heat units) and SONMax (1258.4 heat units). Based on the calculated bioclimatic indices, Central Valley could be considered warmer than Arica and Parinacota, mainly in terms of growing-season indices (GST, GDD and HI), whereas Arica and Parinacota were warmer than the Central Valley for the indices that account for the sum of temperatures in the spring period (SONMean and SONMax).

1.3. Risk indices

The mean value of the number of days with maximum temperatures above 30 °C (T > 30 °C), number of days with maximum temperature above 35 °C (T > 35 °C) and the number of days with minimum temperature below 0 °C (T < 0 °C) were 30.0, 0.7 and 2.4 days respectively, while the standard deviations were 29.0, 1.7 and 3.9 days, respectively (Table 3) across all viticulture regions. Mean values obtained for each weather station for the risk indices are shown in Supplementary Table 2. Lautaro Embalse (Atacama Region) showed the highest risk for T > 30 °C (139.0 days), whereas Coyhaique (Aysén Region) presented the highest risk for T < 0 °C (15.4 days). However, Pencahue (Maule Valley) showed the highest risk for T > 35 °C. Based on the calculated risk indices at the viticulture region level (Table 3), the Atacama Region exhibited the highest risk for T > 30 °C, whereas Central and South Valleys showed a higher risk for T > 35 °C than the rest of the Chilean viticultural regions. The highest frost risk was found in the Aysén region, which accounted for 15.4 days with temperatures lower than 0 °C, while the lowest was presented in Arica and Parinacota, where there were no days with temperatures lower than 0 °C (Table 3).

2. Trend of the indices

2.1. Meteorological indices

Trends in the meteorological indices obtained for the 1985–2015 period from 47 weather stations are shown in Figure 2. Tmin trend values (Figure 2a) fluctuated from –0.075 to 0.082 ºC per year, with negative trends in 55 of the stations % (35.9 % not significant and 19.1 % significant) and positive trends in 45.0 % (34.4 % not significant and 10.6 % significant) of all weather stations (Supplementary Figure 1). A significant negative trend was observed mainly in Northern Chile (Coquimbo Region), presenting a mean value of –0.045 ºC per year. Tmax trend values (Figure 2b) ranged from –0.054 to 0.084 ºC per year, presenting a positive trend in 72.3 % (29.7 % not significant and 42.6 % significant) and a negative trend in 27.7 % (19.2 % not significant and 8.5 % significant) of the total evaluated weather stations (Supplementary Figure 1). The significant positive trends had a mean value of 0.041 ºC per year and were observed for most of the evaluated weather stations, except for those located in Aysén Region. PP trend values (Figure 2c) fluctuated from –11.7 to 7.9 mm per year, presenting a negative trend in 59.6 %, a positive trend in 36.2 % and no trend in 4.3 % of the evaluated weather stations. Based on the data, none of the trends for precipitation presented statistical significance (Supplementary Figure 1).

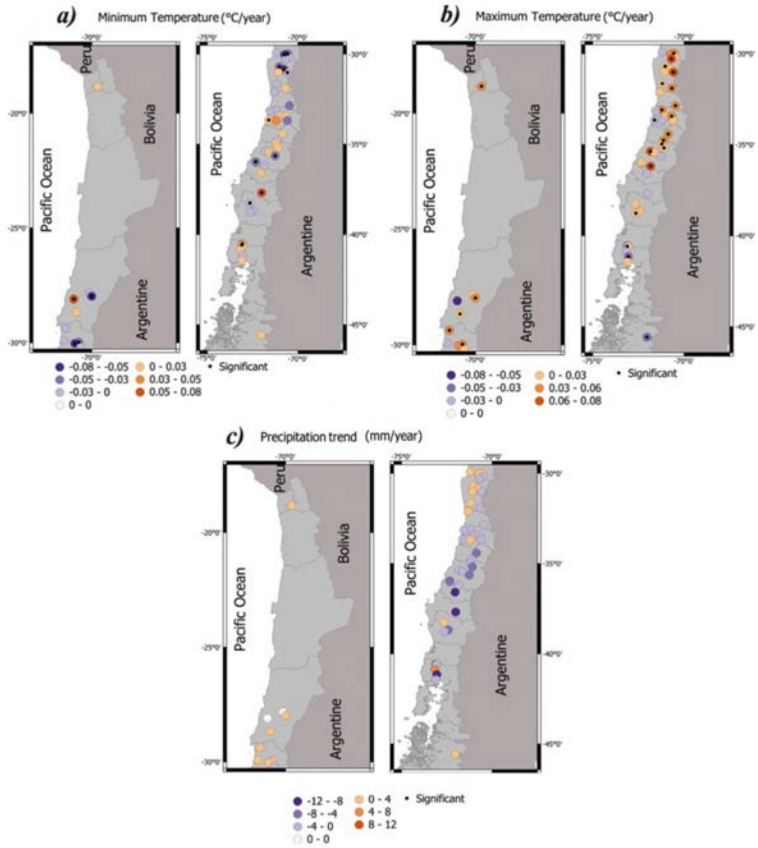

FIGURE 2. Trends for meteorological indices obtained during the 1985–2015 period from 47 weather stations. a) Minimum temperature, b) Maximum temperature and c) Precipitation. The black dot in each figure indicates significant trends (p-value < 0.05).

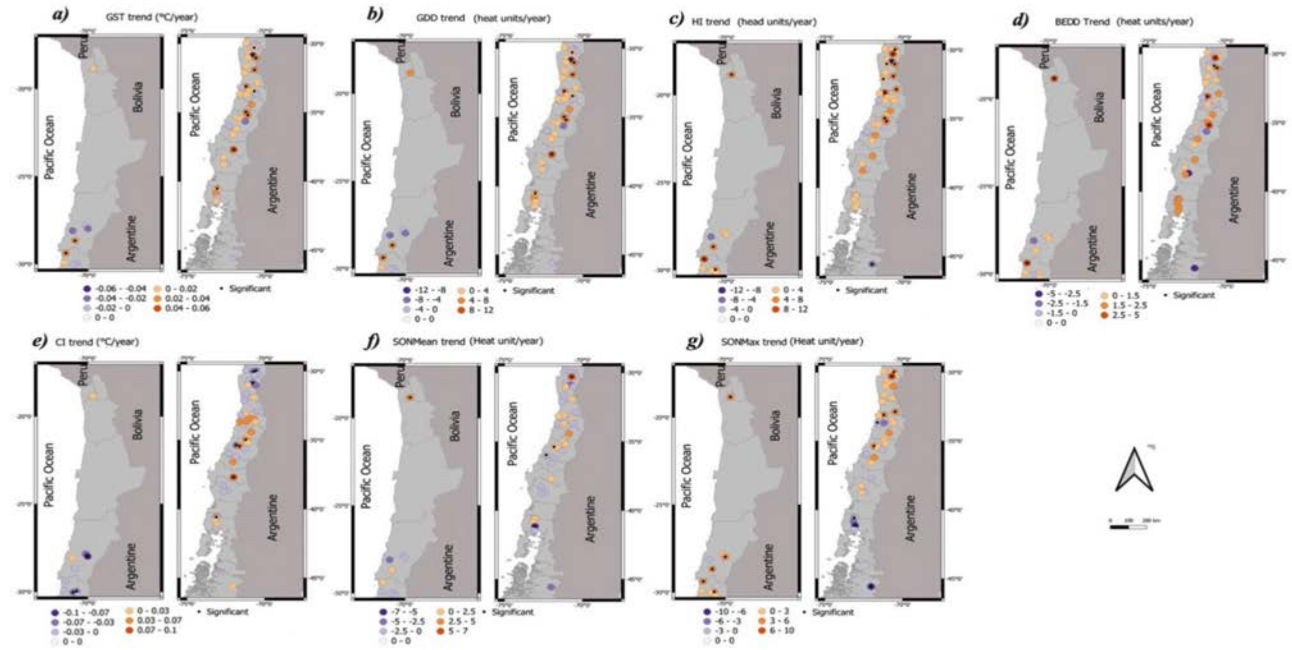

FIGURE 3. Trends for bioclimatic indices obtained during the 1985–2015 period from 47 weather stations. a) GST, b) GDD, c) HI, d) BEDD, e) CI, f) SONMean and g) SONMax. The black dot in each figure indicates significant trends (p-value < 0.05).

2.2. Bioclimatic indices

Trends of bioclimatic indices calculated in the 1985–2015 period from 47 weather stations are shown in Figure 3. GST trend values (Figure 3a) fluctuated from –0.057 to 0.043 ºC per year, with positive trends in 68.1 % (44.7 % not significant and 23.4 % significant) and negative trends in 31.9 % (29.8 % not significant and 2.1 % significant) of the total evaluated weather stations (Supplementary Figure 2). The significant positive trends exhibited a mean value of 0.026 ºC per year and were observed mainly in the Northern and Central Chilean valleys. GDD trend values (Figure 3b) ranged from –11.99 to 8.97 heat units per year, showing positive trends in 70.2 % (46.8 % not significant and 23.4 % significant) and negative trends in 29.8 % (27.7 % not significant and 2.1 % significant) of the total evaluated weather stations (Supplementary Figure 2). The significant positive trends have a mean value of 5.39 heat units per year, and the distribution in Chile was identical to those observed for GST. HI trend values (Figure 3c) fluctuated from –9.72 to 11.76 heat units per year, with positive trends in 83 % (55.3 % not significant and 27.7 % significant) and negative trends in 17.0 % (12.7 % not significant and 4.3 % significant) of the total evaluated weather stations (Supplementary Figure 2). The distribution of significant positive trends in Chile was identical to those observed for GST and GDD, with a mean value of 6.58 heat units per year. BEDD trend values (Figure 3d) varied from –4.26 to 5.16 heat units per year, with positive trends in 70.2 % (57.4 % not significant and 12.8 % significant) and negative trends in 29.8 % (27.7 % not significant and 2.1 % significant) of the total evaluated weather stations (Supplementary Figure 2). The significant positive trends were mainly observed in Northern Chile, with a mean value of 3.34 heat units per year. CI trend values (Figure 3e) ranged from –0.082 to 0.096 ºC per year, with negative trends in 53.2 % (42.6 % not significant and 10.6 % significant) and positive trends in 46.8 % (38.3 % not significant and 8.5 % significant) of the total evaluated weather stations (Supplementary Figure 2). The significant negative trends were mainly observed in Northern Chile, having a mean value of –0.06 ºC per year, while the significant positive trends were observed in the Central Valley, with a mean value of 0.06 ºC per year. SONMean trend values (Figure 3f) fluctuated from –6.74 to 5.03 heat units per year, with negative trends in 59.6 % (55.3 % not significant and 4.3 % significant) and positive trends in 40.4 % (34.0 % not significant and 6.4 % significant) of the total evaluated weather stations (Supplementary Figure 2). The significant positive trends had a mean value of 3.53 heat units per year, and the distribution within Chile did not present a clear pattern based on geographical location. SONTmaxrend values (Figure 3g) ranged from –10.28 to 8.59 heat units per year, with positive trends in 68.1 % (47.0 % not significant and 19.1 % significant) and negative trends in 31.9 % (23.4 % not significant and 8.5 % significant) of the total evaluated weather stations (Supplementary Figure 2). The significant positive trends were mainly observed in Northern and Central Chile, with a mean value of 4.91 heat units per year.

2.3. Risk indices

Trends in risk indices calculated for the 1985–2015 period from 47 weather stations are shown in Figure 4. T > 30 °C

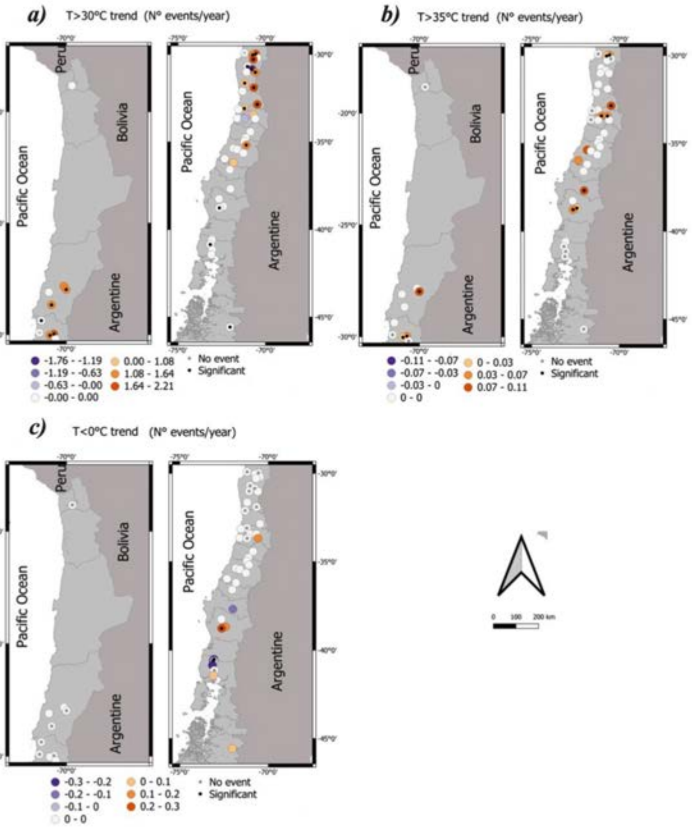

FIGURE 4. Trends for risk indices obtained during the 1985–2015 period from 47 weather stations. a) T > 30 °C, b) T > 35 °C and c) T < 0 °C. The black dot in each figure indicates significant trends (p-value < 0.05). The grey dot in each figure indicates the absence of risk.

trend values (Figure 4a) fluctuated from –1.76 to 2.21 days per year, having positive trends in 70.2 % (36.2 % not significant and 34.0 % significant) and negative trends in 8.5 % (6.4 % not significant and 2.1 % significant) of the total evaluated weather stations (Supplementary Figure 3). In addition, it was observed that 19.1 % of the weather stations had no trends, while in 2.1 % of them, the risk was not recorded (no event). The significant positive trends were observed mainly in Northern and Central Chile, with a mean value of 1.05 days per year. T > 35 °C trend values (Figure 4b) varied from 0.00 to 0.11 days per year, with positive trends in 23.4 % (4.3 % not significant and 19.1 % significant) of the total evaluated weather stations (Supplementary Figure 3). T > 35 °C index negative trends were not observed at any stations. In addition, no trend was observed in 57.4 % of the weather stations, and the risk was not recorded (no event) in 19.1 % of the weather stations. The significant positive trends were observed mainly in Northern and Central Chile, with a mean value of 0.053 days per year. T < 0 °C trend values (Figure 4c) ranged from –0.26 to 0.28 days per year, having positive trends in 10.6 % (8.5 % not significant and 2.1 % significant) and negative trends in 10.6 % (6.3 % not significant and 4.3 % significant) of the total evaluated weather stations (Supplementary Figure 3). In addition, no trends were observed in 48.9 % of the weather stations, and the risk was not recorded (no event) in 29.8 % of the weather stations.

3. Variability of the indices

3.1. Meteorological indices

The variability (CV) of meteorological indices calculated for the 1985–2015 period from 47 weather stations are shown in Figure 5. Tmin CV (Figure 5a) fluctuated from 4.3 to 16.4 %, and the weather stations that exhibited a high variability (CV > 10 %) were distributed across all Chilean viticultural regions. Tmax CV (Figure 5b) ranged from 1.6 to 5.9 %, with weather stations with high variability (CV > 4 %) being distributed mostly in Southern Chile. Tmin CV was approximately three times higher compared to those observed for the Tmax CV in the period under study. PP (Figure 5c) CV varied from 13.2 to 144.1 %, and a variability gradient was observed across Chile, decreasing from the north to the south.

3.2. Bioclimatic indices

The variability (CV) of the bioclimatic indices calculated in the 1985–2015 period from 47 weather stations are shown in Figure 6. GST CV (Figure 6a) ranged from 1.8 to 5.9 %, and the weather stations that exhibited the highest variability (CV > 3%) were in the Chilean Central Valley. GDD CV (Figure 6b) varied from 3.8 to 28.5 %, with the weather

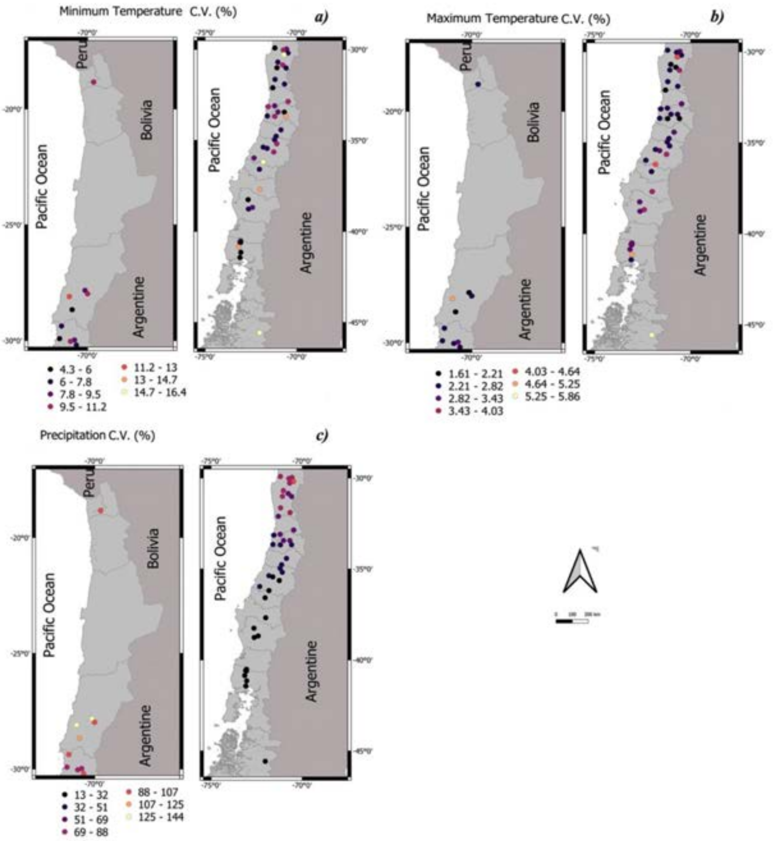

FIGURE 5. Variability (Coefficient of variation, %) of meteorological indices obtained during the 1985–2015 period from 47 weather stations. a) Minimum temperature, b) Maximum temperature and c) Precipitation.

stations that showed the highest variability (CV > 10 %) found in Southern Chile. HI CV (Figure 6c) fluctuated from 2.4 to 19.9 %, and the weather stations that exhibited the highest variability (CV > 8 %) were mainly located in Northern and Central Chile. BEDD CV (Figure 6d) ranged from 0.6 to 30.6 %, with the weather stations that showed the highest variability (CV > 15 %) mainly located in Southern Chile. CI CV (Figure 6e) fluctuated from 6.6 to 22.2 %, and the weather stations that showed the highest variability (CV > 15 %) were mainly located in Central and Southern Chile. SONMean CV (Figure 6f) varied from 2.7 to 8.1 %, with the weather stations that had the highest variability (CV > 5 %) being mainly located in Central and Southern Chile. SONMax CV (Figure 6g) fluctuated from 2.0 to 8.5 %, and the weather stations that showed the highest variability (CV > 6 %) were mainly located in Southern Chile.

3.3. Risk indices

The variability (CV) of risk indices calculated in the 1985–2015 period from 47 weather stations are shown in Figure 7. T >30 °C, T > 35 °C and T < 0 °C CV (Figure 7) varied from 0 to 435 %, from 0 to 548 % and from 0 to 538 %, respectively. The weather stations that exhibited the highest variability (CV > 300 %) were mainly located in Northern and Central Chile. The high values of the variability of these indices were related to years when extreme events related to the above-mentioned risks events did or did not occur.

4. Relationship between mean and geographic variables of weather stations

The relationship between mean climate characteristics and geographic variables of the weather stations are shown in Figure 8. Concerning meteorological indices (Figure 8a), principal component 1 (PC1) explained 66.5 % of the variance, and PC2 explained 20.6 %, representing 87.1 % of the total variance. PC1 was positively related to geographic variables such as latitude, longitude, and elevation, Tmin and Tmax, and negatively to PP. PC2 was positively correlated to the distance of the station to the Pacific Ocean. Regarding the correlations between the mean of the meteorological indices and geographical variables, Tmin and Tmax were positively related to latitude, longitude, and elevation, while PP was negatively related to latitude, longitude, and elevation (Supplementary Table 4). Concerning bioclimatic indices (Figure 8b), PC1 explained 74.7 % of the variance, and PC2 explained 12.5 %, representing 87.2 % of the total variance. PC1 was positively correlated to all bioclimatic indices and geographic variables, while PC2 was positively related to the distance of the station to the Pacific Ocean. Regarding the correlations between the bioclimatic indices and geographical variables, all the indices showed positive

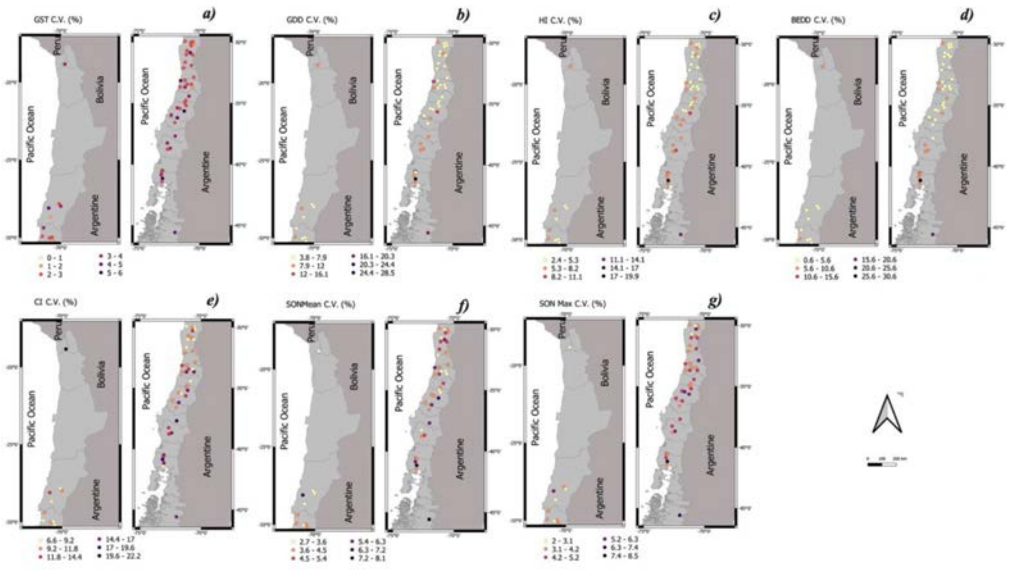

FIGURE 6. Variability (Coefficient of variation, %) of bioclimatic indices obtained during the 1985–2015 period from 47 weather stations. a) GST, b) GDD, c) HI, d) BEDD, e) CI, f) SONMean and g) SONMax.

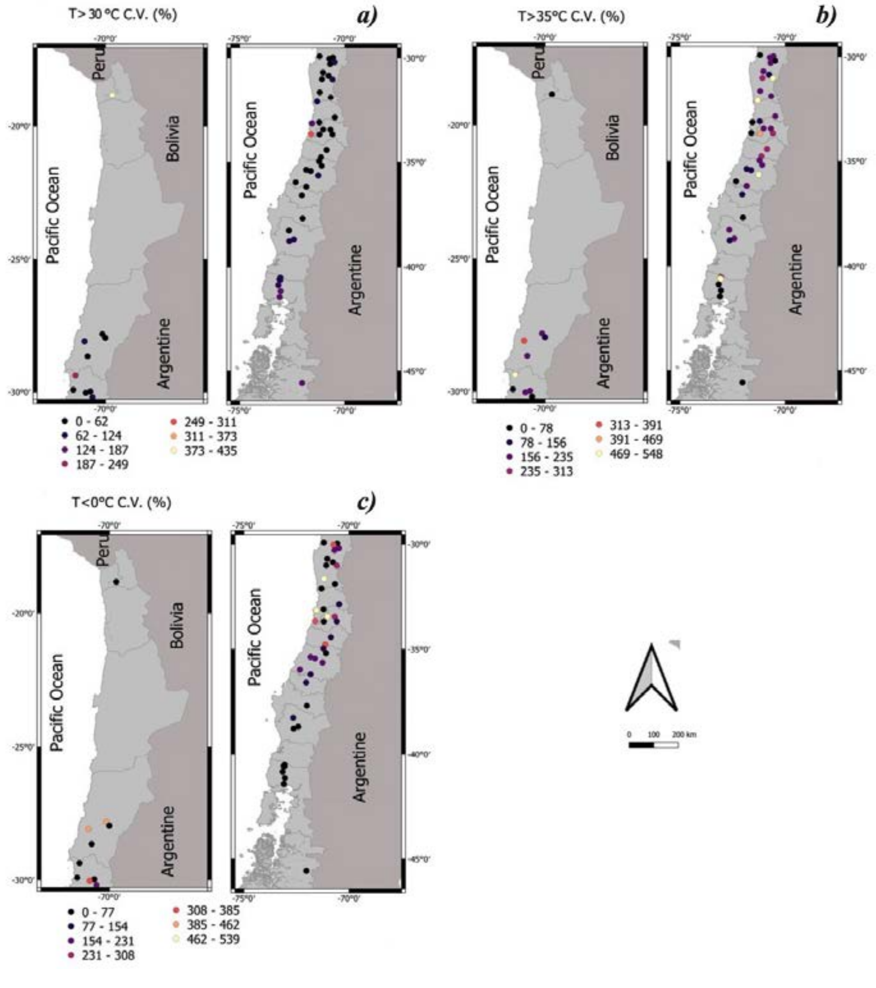

FIGURE 7. Variability (Coefficient of variation, %) of risk indices obtained during the 1985–2015 period from 47 weather stations. a) T > 30 °C, b) T > 35 °C and c) T < 0 °C.

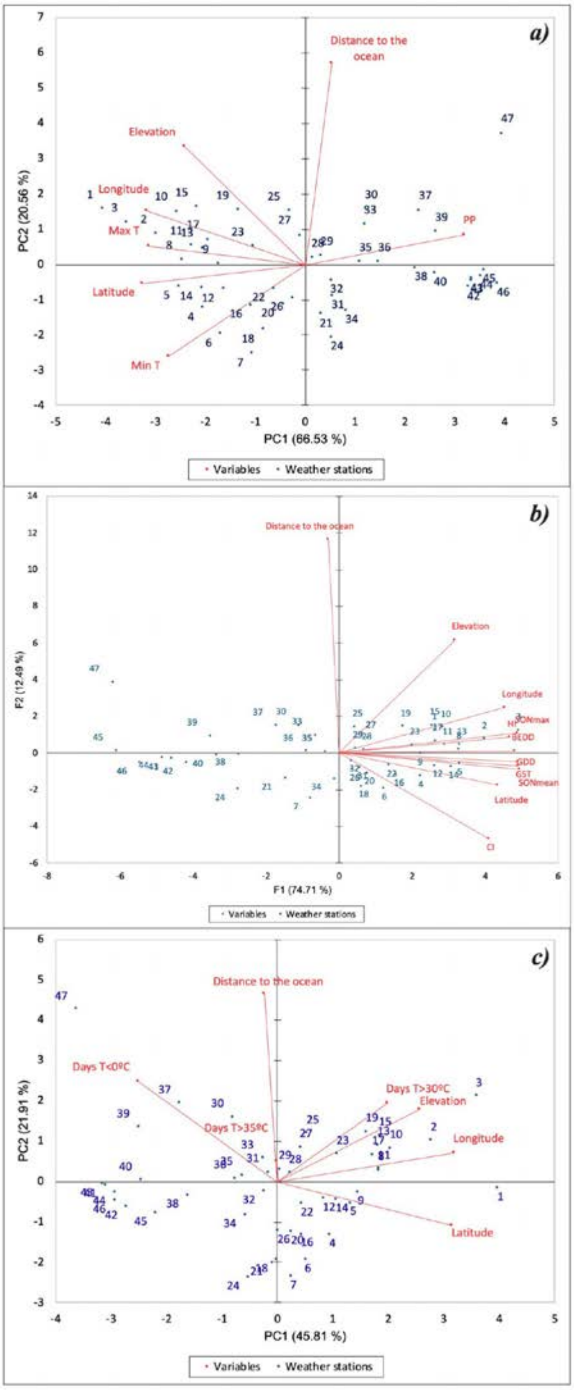

FIGURE 8. Principal component analysis (PCA) between mean station characteristics and geographic variables for the 47 weather stations. a) Meteorological indices, b) Bioclimatic indices and c) Risk indices. PC: Principal component. Abbreviation according to Table 2.

correlations to latitude, longitude, and elevation, while CI was negatively related to the distance of the station to the Pacific Ocean (Supplementary Table 4). Concerning risk indices (Figure 8c), PC1 explained 45.8 % of the variance, and PC2 explained 21.9 %, representing 67.7 % of the total variance. PC1 was positively related to geographic variables and T > 30 °C. PC2 was positively correlated to the distance of the station to the Pacific Ocean. T > 35 °C (mean) was represented in PC3 (data not shown). Regarding the correlations between the risk indices (mean) and geographical variables, T > 30 °C was positively correlated to the geographical variables (except to the distance to the Pacific Ocean), while T < 0 °C was negatively related to latitude and positively to longitude and the distance of the station to the Pacific Ocean (Supplementary Table 4).

5. Relationship between trends and geographic variables of weather stations

The relationship between climate trends and geographic variables of weather stations are shown in Figure 9.

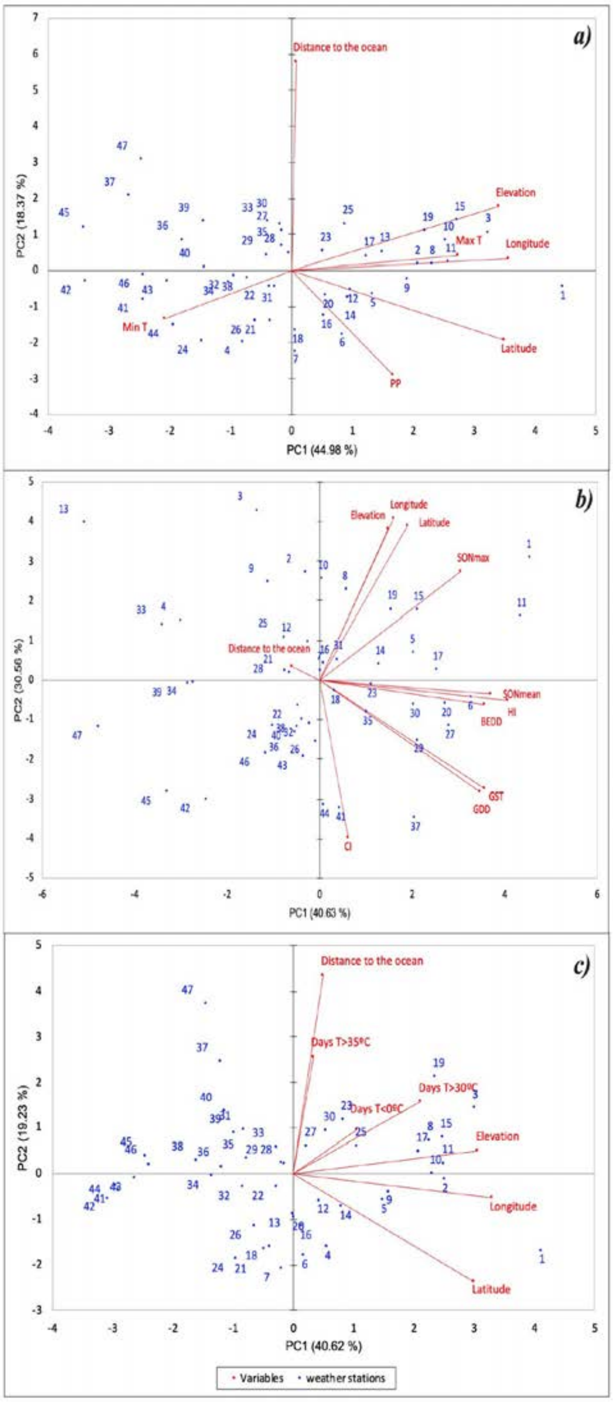

FIGURE 9. Principal component analysis (PCA) between station trends and geographic variables of the 47 weather stations. a) Meteorological indices, b) Bioclimatic indices and c) Risk indices. PC: Principal component. Abbreviation according to Table 2.

Concerning meteorological indices (Figure 9a), PC1 explained 45.0 % of the variance, and PC2 explained 18.4 %, representing 63.4 % of the total variance. PC1 was positively related to geographic variables and Tmax, while PC2 was positively related to the distance of the station to the Pacific Ocean. Regarding the correlations between the trends of the meteorological indices and geographical variables, Tmax was positively related to the geographic variables, while Tmin was negatively related to elevation. PP was positively correlated to latitude (Supplementary Table 5). Concerning bioclimatic indices (Figure 9b), PC1 explained 40.6 % of the variance, and PC2 explained 30.6 %, representing 71.2 % of the total variance. PC1 was positively related to almost all bioclimatic indices except CI, while PC2 was positively related to geographic variables and CI. Regarding the correlations between the trends of the bioclimatic indices and geographical variables, only CI and SONMax showed significant correlations with the geographic variables (Supplementary Table 5). Concerning risk indices (Figure 9c), PC1 explained 40.6 % of the variance, and PC2

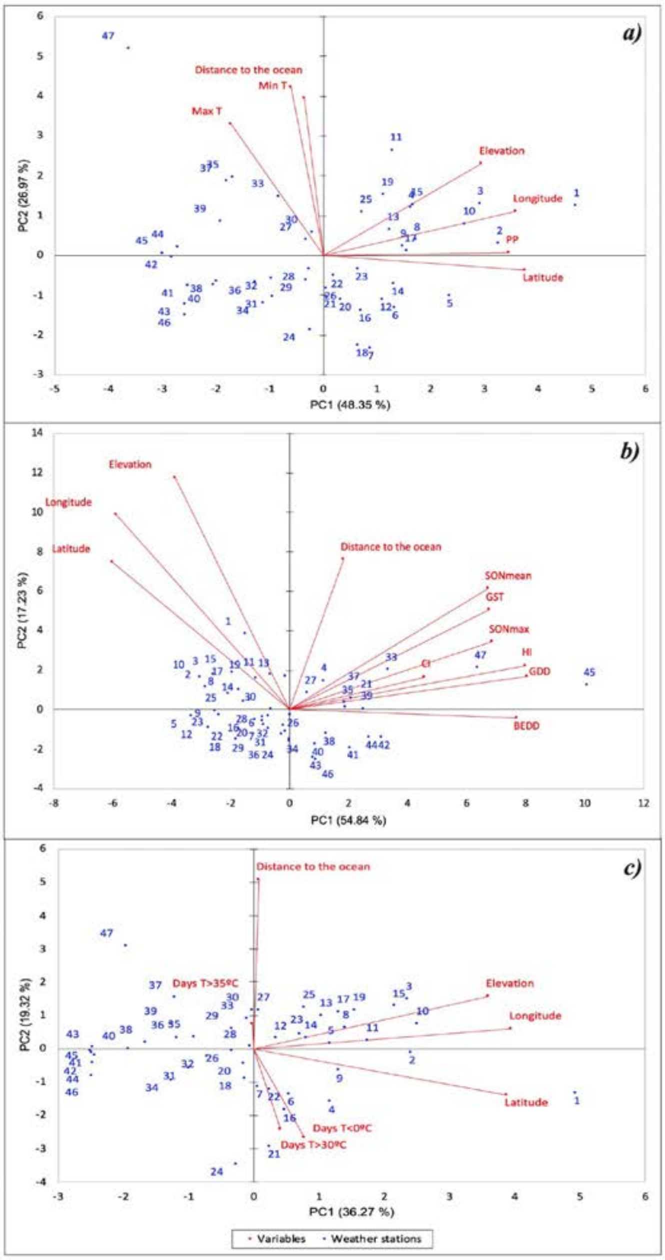

FIGURE 10. Principal component analysis (PCA) between climate variability and geographic variables of the 47 weather stations. a) Meteorological indices, b) Bioclimatic indices and c) Risk indices. PC: Principal component. Abbreviation according to Table 2.

explained 19.2 %, representing 59.8 % of the total variance. PC1 was positively related to geographic variables, while PC2 was positively related to the distance of the station to the Pacific Ocean. Risk indices trends were represented in the PC3, PC4 and PC5. Days T > 30 ºC trend was related to the geographic variables (except for the distance to the Pacific Ocean, Supplementary Table 5).

6. Relationship between variability and geographic variables of weather stations

The relationship between climate variability and the geographic variables of weather stations are shown in Figure 10. Concerning meteorological indices (Figure 10a), PC1 explained 48.4 % of the variance, and PC2 explained 27.0 %, representing 75.4 % of the total variance. PC1 was positively related to the geographic variables and PP, while PC2 was positively related to the distance of the station to the Pacific Ocean, Tmin and Tmax. Regarding the correlations between the variability of the meteorological indices and geographical variables, Tmax was positively related to the distance of the station to the Pacific Ocean and negatively related to latitude and longitude. Tmin was positively related to the distance of the station to the Pacific Ocean, while PP was positively related to latitude, longitude and elevation (Supplementary Table 6). Concerning bioclimatic indices (Figure 10b), PC1 explained 54.8 % of the variance, and PC2 explained 17.2 %, representing 72.0 % of the total variance. PC1 was positively related to most of the calculated bioclimatic indices, except CI, and negatively to latitude and longitude. PC2 was positively related to elevation. Regarding the correlations between the variability of the bioclimatic indices and geographical variables, latitude was negatively related to most of the bioclimatic indices, except GST. Longitude was negatively related to most of the bioclimatic indices, except SONMean. Elevation was negatively related to GDD and BEDD, while the distance of the station to the Pacific Ocean was positively related to SONMean and SONMax (Supplementary Table 6). Concerning risk indices (Figure 10c), PC1 explained 36.3 % of the variance, and PC2 explained 19.3 %, representing 55.6 % of the total variance. PC1 was positively related to the geographic variables, while PC2 was positively related to the distance of the station to the Pacific Ocean. Risk index variability was represented in the PC3 and PC4. None of the risk indices variability was related to the geographic variables (Supplementary Table 6).

DISCUSSION

This is the first study that describes the climatic conditions of viticulture in Chile, from Codpa (18º63' S) to Coyhaique (45º57' S), considering three types of weather and climate indices and one of the most extensive databases available today. For the mean values, the Chilean viticultural production can be considered a warm climate (GST = 17.04 ºC), as was previously confirmed by Montes *et al*. (2012) for Aconcagua, Maipo and Cachapoal Valleys. Climate trends in Chile indicated that from 1985 to 2015, the minimum temperature decreased by 0.33 ºC (in 14/47 sites), whereas the maximum temperature increased by 0.83 ºC (in 24/47 sites). In addition, GST, GDD, HI, BEDD, SONMean and SONMax increased by 0.58 ºC (12/47 sites), 118.29 heat units (12/47 sites), 140.57 heat units (15/47 sites), 79.72 heat units (7/47 sites), 8.42 heat units (5/47 sites) and 45.17 heat units (13/47 sites), whereas CI decreased by 0.19 ºC (9/47 sites) for the same period. These trends (except for CI) are also reported in the scientific literature in different viticultural regions. In this way, observed changes in 36 % of viticultural regions in the world have shown an increase in the GST by 1.3 ºC (period 1950– 2000) (Jones *et al*., 2005).

Climate change has provoked changes in viticultural suitability over the last decades for many wine regions, and it has been anticipated to exacerbate these trends for wine production (Santos *et al*., 2020). Stations from Elqui and Marga-Marga valleys changed their viticultural suitability, according to the Jones (2006) classification, from intermediate (GST: 16.8 ºC) to warm (GST: 19.4 ºC) climate; stations from Limarí, Choapa and Maipo valleys changed from warm (GST: 17.9 ºC) to hot (GST: 20.1 ºC) climate; a station from Biobío Valley changed from cool (GST: 14.9 ºC) to warm (GST: 17.2 ºC) climate; and a station from Osorno Valley can currently cultivate the vine in a cool climate (GST: from 12.7 to 14.9 ºC). Some varieties, such as Sauvignon blanc, Chardonnay, Riesling, and Pinot noir, are mostly cultivated close to the Quilaco station (Biobío Valley). However, according to our results, this viticultural zone may not be suitable for these short-season varieties, while varieties with higher thermal accumulation, such as Semillon, Tempranillo or Merlot, may be suitable for this area.

Despite that there is a pattern of increasing temperatures from north to south that is clearly evidenced in the mean values of the meteorological and bioclimatic indices, climatic variability can cause significant distortions in these patterns. Indeed, despite the fact that the warmest areas are in the regions of higher latitudes, the central and southern areas show higher temperature peaks. In fact, the high-temperature records are greater in the zones located in the Central Valley and in the South compared to northern viticultural valleys. In addition, Quilaco (37º69'S) was the third station that registered a greater number of days with temperatures above 35 ºC. In this sense, the South viticultural zone is characterised by using short-growing season varieties, such as Pinot noir, Chardonnay, and Sauvignon blanc. Thus, the difference in the spatial pattern observed between the bioclimatic indices that utilise the growing season (GST, GDD, HI and BEDD) compared to the indices that focus on spring (SONMean and SONMax) suggests that the heat accumulation in the northern zone is more homogeneous, while in the central and southern zones, it is concentrated in the summer, which has been previously reported by Gutiérrez and Hajek (1979). This phenomenon may induce different maturation patterns since, in the first case, it is a gradual process, while in the second, the process has marked fluctuations in temperature along berry ripening. In this fashion, it is possible to suggest that in the South and Central valleys, vine technological maturity may occur in a short period compared to the Northern valleys. Several reports have shown a decoupling between technological and phenolic maturities in vineyards established in Mediterranean climates (Martínez de Toda and Balda, 2015; Salazar-Parra *et al*., 2018), which may be intensified in South and Central valleys compared to the north. Gutiérrez-Gamboa *et al*. (2021) mentioned that this decoupling might result in two devastating consequences for the wine industry. Firstly, if grapes are harvested at the optimal technological maturity, in terms of soluble solids, acid and pH, grape quality may not be optimum in terms of phenolic compounds and their related sensory attributes, which may induce detrimental consequences on colour, astringency and ageing in wines. Furthermore, if the winegrowers try to postpone the harvest date to reach higher content of phenolic compounds, the berries may become dehydrated and reach higher soluble solids content and, as a consequence, produce wines with higher alcoholic content and astringency. This decoupling has also been reported for other relevant metabolites, such as organic acids, amino acids, and volatile compounds (Bonada *et al*., 2015; Gutiérrez-Gamboa *et al*., 2018; Delrot *et al*., 2020). Based on this, it would be interesting to study this phenomenon in vineyards cultivated in the Northern valleys and compare them to those established in the Central and South valleys.

As expected, the mean annual precipitation generally increases, and the mean annual temperature decreases from north to south latitude in Chile (Gutiérrez and Hajek, 1979). As the daily temperature is relatively high, a low night temperature is essential to keep a desirable grape quality in terms of pH, phenolic and aromatic compounds (Tonietto and Carbonneau, 2004). Some stations such as Lautaro Embalse (27º98' S; Atacama), Rivadavia (29º98'; Coquimbo), Vicuña (30º03' S; Coquimbo), Caren (30º83'; Coquimbo) and Pencahue (35º37'; Central Valley) exhibited a negative trend for CI which in most of the cases coincided to the stations that showed the highest number of days with temperatures greater than 30 ºC (Supplementary Table 2). Coquimbo Region is characterised by the production of raisins, table grapes and Pisco, while Pencahue is known for producing good Cabernet Sauvignon wines. Based on this, these areas would have the potential to produce wine products with high quality in terms of amino acids and phenolic and volatile compounds.

Several authors have reported higher maximum temperatures, lower rainfall, and an increase in days with temperatures above 30 °C in the Central valleys (Orrego-Verdugo *et al*., 2021; Burger *et al*., 2018). In this sense, the trends for the minimum temperatures observed in this study deserve attention since they have a pattern contrary to the logic of the effects of global warming in many seasons. This phenomenon may be explained by the intensification of the Southeast Pacific Anticyclone and the consequent cooling of the coastal zone, which occurs especially in Northern Chile. The above is projected by the IPCC models (IPCC, 2021) and verified based on measurements and relationships with atmospheric indices (Schultz *et al.*, 2012). Indeed, the principal component analysis (PCA) revealed strong relationships between these trends and the distance of the site to the Pacific Ocean (Supplementary Tables 4 to 6). In a terroir study, Gutiérrez-Gamboa and Moreno-Simunovic (2018) reported that in the Maule Valley, the vines growing in the sites closer to the Pacific Ocean, such as in Truquilemu and Ciénaga de Name, exhibit a higher concentration of several amino acids and volatile compounds in grapes and wines, while the vines growing in the sites further east, inland towards the intermediate depression, provide grapes and wines with higher alcohol and phenolic concentrations.

Research for the future should try to understand the impacts of climatic variability on vine phenology, yield, grape quality and harvest date using a historical database such as that used in this research, which currently is difficult to get locally. In this fashion, this report only provided an approach regarding climatic information. Notably, Chile presents a wide variety of climates, and in some cases, the calculation of bioclimatic indices may not correspond to this reality. Therefore, future studies should determine the effect of adjusting the index calculation dates on the observed trends and variability.

CONCLUSIONS

In conclusion, from north to south latitudes in Chile, the mean annual precipitation increases while the mean annual temperature decreases. Based on meteorological data, the warmest viticultural zone in the country was Atacama, whereas the coldest zone was Aysén. In addition, the rainiest region was Austral, while the driest was Arica and Parinacota. Based on bioclimatic indices, Central Valley could be considered warmer than Arica and Parinacota, mainly in terms of growing-season indices (GST, GDD and HI), whereas Arica and Parinacota was warmer than the Central Valley for the indices that account for the sum of the temperatures in the spring period (SONMean and SONMax). Based on risk indices, Atacama Region presented the highest risk for T > 30 °C, whereas the Central and South Valleys showed a higher risk for T > 35 °C. The highest frost risk was found in the Aysén region, while the lowest was in Arica and Parinacota, where temperatures lower than 0 °C do not typically occur.

The trends indicated that minimum temperature significantly decreased by 0.33 ºC, while maximum temperature significantly increased by 0.83 ºC over the 30-year period of this study.

None of the trends for precipitation exhibited statistical significance in Chile. Bioclimatic indices, such as Growing Season Temperature (GST), Growing Degree-Days (GDD), Huglin Heliothermal Index (HI), Biologically Effective Degree-Days (BEDD), Mean Spring Temperature Summation (SONMean) and Maximum Spring Temperature Summation (SONMax) significantly increased by 0.58 ºC, 118.29 heat units, 140.57 heat units, 79.72 heat units, 8.42 heat units and 45.17 heat units, respectively, while Cold Night Index (CI) decreased by 0.19 ºC over the 30 year period of this study. Some stations showed a negative trend on CI, in most of the cases, coincided with the stations that presented the highest number of days with temperatures higher than 30 ºC. Locations in some valleys, such as Coquimbo and Aconcagua valleys, changed from intermediate to warm climates, while others from Coquimbo and Central valleys changed from warm to hot climates during the 30-year period of this study. A station located in Quilaco changed from a cool to a warm climate, while a station located in Osorno changed from 12.7 to 14.9 ºC (without classification to cool climate). PCA analysis reported that meteorological variables showed a strong relationship to the distance of the site to the Pacific Ocean, which supports previous studies. This was the first study that analysed the trend and variability of the national viticultural zones from north to south, providing valuable and significant information about the effect of global warming in the viticultural zones of Chile.

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