Bragantia
ISSN: 0006-8705
editor@iac.sp.gov.br
Instituto Agronômico de Campinas
Brasil

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Bragantia, vol. 73, núm. 3, 2014, pp. 327-334
Instituto Agronômico de Campinas
Campinas, Brasil

http://dx.doi.org/10.1590/1678-4499.0127

Climate trends in a non-traditional high quality wine producing region

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Received: *Apr. 20, 2014;* **Accepted:** *June 24, 2014*

Agrometeorology | Article

Abstract

The global warming may put pressure over some world's highest quality wine producing regions. This fact indicates the need to evaluate the presence of climate change in non-traditional wine producing regions of the Globe. Therefore, the goals of this study were to detect trends in rainfall and air temperature series obtained from three locations of the eastern part of the State of São Paulo, Brazil (a non-traditional high quality wine producing region) and to evaluate the effect of the detected climate trends on agrometeorological indices frequently used to indicate suitable areas for wine production. The trend analyses were applied to maximum and minimum air temperature series, rainfall series and to the following agrometeorological parameters: heliothermal index, cool night index and growing degree-days. These three indices were selected due to their previous use in studies that address the effect of regional climate conditions on the general wine style. The analyses took into account the grape phenological aspects for both summer and winter growing seasons. The results found in this study support the hypothesis of the presence of climate trends in the wine producing regions of the eastern part of the State of São Paulo-Brazil. These trends are mostly linked to changes in the minimum air temperature. The results also reveal a shortening in the duration of grapevines phenological phases and a change to warmer conditions during the ripening Months. These changes are consistent with the climate changes observed in other wine producing regions of the world and may negatively affect the wine production of the eastern part of the State of São Paulo.

Key words: global warming, biometeorological indices, Mann-Kendall.

Tendências climáticas em uma região não tradicional de produção de vinhos de alta qualidade

Resumo

O aquecimento global pode afetar negativamente regiões tradicionalmente vitícolas do globo terrestre. Esse fato indica a necessidade de verificar a presença de alterações nos padrões climáticos em regiões alternativas (ou não tradicionais) para o cultivo de uvas para vinhos finos. Assim, os objetivos desse estudo foram detectar tendências climáticas em séries de temperatura do ar e precipitação pluvial em três localidades da parte leste do estado de São Paulo e avaliar os efeitos dessas alterações em índices agrometeorológicos frequentemente utilizados na indicação de áreas favoráveis à produção de uvas para vinho. As análises de tendência foram aplicadas a séries de temperatura máxima e mínima, a séries de precipitação pluvial e aos seguintes índices, selecionados por serem usualmente utilizados em estudos que abordam o efeito do clima regional sobre a produção de uvas para vinho: heliotérmico, frio noturno e graus-dia. Consideraram-se os aspectos fenológicos em safras de verão e inverno. Os resultados suportam a hipótese de presença de mudanças climáticas na região do estudo, indicando que ela é fundamentalmente relacionada a alterações temporais na temperatura mínima do ar. Observou-se também o encurtamento da duração das fases fenológicas da videira e uma mudança para uma condição de temperatura do ar mais elevada ao longo do período de maturação. Essas alterações climáticas são consistentes com as observadas em outras regiões vitícolas do globo terrestre.

Palavras-chave: aquecimento global, índices biometeorológicos, Mann-Kendall.

1. INTRODUCTION

An important step of the Global warming studies is to evaluate its possible regional impacts. In this sense, the agrometeorological researches need to evaluate the possible impacts of the current climate change on agriculture (Zullo Junior et al., 2006) because any change in the climate pattern of a given region may impact the crop development (Gouvêa et al., 2009). Regarding the influence of the climate on grape wine production, it is well known that the regional atmospheric conditions strongly influence the regional wine style (Jones et al., 2005; Orlandini et al., 2009).

Based on the above-mentioned assumption, several studies have evaluated the significance of regional climate trends to better understand their possible impacts on the grapevine phenology. According to Jones et al. (2005) the majority of the world's highest quality wine-producing regions experienced growing season warming trends from 1950 to 1999. Orlandini et al. (2009) analyzed climate and agrometeorological time series of Tuscany, Central Italy. The results found by this study indicated the presence of a significant warming trend and a general shortening in the duration of grapevine phenological phases. A change to warmer climate conditions is also observed by Tomasi et al. (2011) for the Veneto Region of Italy and by Ramos et al. (2008) for the northeast Spain. Finally, by using a coupled atmosphere-ocean general circulation model (HadCM3) developed by Gordon et al. (2000), Jones et al. (2005) and Pope et al. (2000), projected for several grapevine producing regions of the world an average warning of, approximately, 2 °C during the next 50 years. According to these authors, this increase on the air temperature patterns may put pressure over some grapevine producing regions of the World (Jones et al., 2005).

Back et al. (2012) assessed the significance of trends in meteorological series as well as in agrometeorological parameters obtained from grapevine producing region of Goethe Grape Valley, State of Santa Catarina, Brazil. These authors detected significant warming trends in the minimum air temperature series and a significant shortening in the length of the period between pruning and harvest. A similar study was carried out by Back et al. (2013) for the grape producing location of the Vale do Rio Peixe, State of Santa Catarina, Brazil. This latter study also revealed a significant shortening in the length of the period associated with pruning, flowering and harvesting. Back et al. (2013) also detected increasing trends in both maximum and minimum air temperature series.

The abovementioned evidences of warming trends observed in virtually all world's highest quality vine-producing regions of the Globe supports the assumption that the wine industry may be required to find new locations for viticulture (Falcão et al., 2010). Accordingly, we posed the following question: Is there any evidence of climate change that may impact the wine production of non-traditional areas? In order to shed some light into this issue the goals of this study were (i) to detect trends in rainfall and air temperature series obtained from three locations of the eastern part of the State of São Paulo (a nontraditional wine producing region) and, (ii) to evaluate the effect of these climate trends on agrometeorological indices frequently used to indicate suitable areas for wine production.

2. DATA AND METHODS

The air temperature data were obtained from the weather stations of Campinas (22°54'S; 47°05'W; 669m; 1945-2012), Jundiaí (23°06'S; 46°55'W; 725m, 1968-2012) and Monte Alegre do Sul (22°41'S; 46°40'; 782m, 1945-2012). These three weather stations belong to the Agronomic Institute of Campinas (IAC/APTA-SAA) and are located at the boundaries of the Tropic of Capricorn. The monthly rainfall data (PRE) observed in these locations can be considered as having been drawn from a 2-parameter gamma distribution as well as a 3-parameter Pearson Type-III distribution (Blain et al., 2009; Blain, 2012). The shape of these monthly probability functions vary from a strongly skewed distribution similar to those observed in arid climate (Winter Season) to a bell-shaped distribution similar to those observed in equatorial climate (Summer Season). According to Blain (2011) both maximum (Tmax) and minimum (Tmin) monthly air temperature series can be considered as having been drawn from a normal distribution.

The trend analyses were applied to the Tmax, Tmin and Pre series and to the following agrometeorological parameters: heliothermal index (HI), cool night index (CI) and growing degree-days (GDD). These three temperature-based indices were selected due to their previous use in studies that address the effect of regional climate conditions on the general wine style (Anderson et al., 2012; Back et al., 2012; 2013; Tonietto and Carbonneau, 2004). Also, the use of these three temperature-based indices relies on the fact that the air temperature is one of the most important factors affecting the quality of vinegrapes production (Hall and Jones, 2010). The grapes of the Eastern part of the State of São Paulo have been grown in two different periods of the year. Thus, the trend analyses were carried out taking into account the grape phenological aspects for both summer (August to January) and winter (January to June) growing seasons. The GDD was calculated using equation 1 with a base temperature (Tb) equal to 10 °C (Anderson et al., 2012, among many others).

$$GDD = \left(\frac{T\,max + T\,min}{2}\right) - Tb \qquad (1)$$

Initially proposed by Tonietto and Carbonneau (2004), the HI (Equation 2; Table 1) is largely used in viticulture studies

Table 1. Classification system of the Heliothermal Index (HI)

Class of viticultural climate*	Acronym	Class interval
very cool	HI-3	HI ≤ 1500
Cool	HI-2	1500 < HI ≤ 1800
Temperate	HI-1	1800 < HI ≤ 2100
Warm temperate	HI+1	2100 < HI ≤ 2400
Warm	HI+2	2400 < HI ≤ 3000
Very warm	HI+3	3000 < HI

*Tonietto and Carbonneau (2004).

(Anderson et al., 2012; Back 2012; 2013; Orlandini et al., 2009). The HI and GDD equations are similar to each other (Anderson et al., 2012) but, the HI gives more emphasis to the effect of the Tmax on the crop development. Equation 2 also presents a k factor that take into account the length of the days at the analyzed site (latitude). By following Hall and Jones (2010) and considering the latitude of the three location of this study, we set k to 1. T and Tx are, respectively, the mean and maximum monthly air temperature (°C).

$$HI = \sum_{harvest}^{pruning} \frac{\left[(T-10)+(Tx-10)\right]}{2} * k \qquad (2)$$

The cool night index (CI; Table 2) is based on the average minimum air temperature (T_{minrip}) obtained during the ripening month.

The Mann-Kendall test (MK; Kendall and Stuart, 1967; Mann, 1945) is a non-parametric test widely used to detect trends in meteorological, hydrological and agro-meteorological time series (Back et al., 2012; 2013; Blain, 2013, among many other). Positive (negative) MK values indicate the presence of increasing (decreasing) trends. However, one important drawback of the MK test is that it was originally designated for uncorrelated data (Von Storch and Navarra, 1995). In this view, it is worth emphasizing that (agro) meteorological variables usually exhibit some form of temporal persistence (Blain, 2012; Wilks, 2011). In order to deal with the possible presence of serial correlation, we applied the original MK test as well as a modified form of this test, called "Pre-Whitening Mann-Kendall test" (MK-PW) to evaluate the presence of trends in all series of this study. Initially suggested by Von Storch and Navarra (1995), the MK-PW removes the lag-1 auto-correlation coefficient (r_{data}) from the data sample prior to the trend analysis (Yue et al., 2002). The r_{data} was calculated as described in Wilks (2011). Further information regarding the MK and MK-PW can be found in several studies including Yue et al. (2002).

The magnitude of the detected trends namely, its long-term rate of change per time unit, were estimated using the method called "Theil Sen Slope" (TSA; Sen, 1968). The TSA is a robust non parametric estimate of the slope of the trend frequently used in (agro/hydro) metorological studies (Back et al., 2012; 2013, among many others). All statistical tests were performed at the 5% significant level.

Table 2. Classification system of the Cool Night Index (CI)

Class of viticultural climate*	Acronym	Class interval
Warm night	CI-2	T_{minrip}>18ºC
Temperate nights	CI-1	14°C<T_{minrip} ≤ 18°C
Cool nights	CI+1	12°C< T_{minrip} ≤ 14°C
Very cool nights	CI+2	T_{minrip}<12°C

*Tonietto and Carbonneau (2004).

3. RESULTS AND DISCUSSION

The average value of the Tmax, Tmin and Pre series observed during each growing season over the 68 (51) years are presented in table 3.

Regarding the HI classification system, there is no remarkable difference between the climate conditions observed during the summer (August to January) and winter (January to June) growing seasons (Table 3). This feature is due to the fact that the HI calculation (equation 2) gives equal weighs to the air temperature conditions observed during all different stages of the phenological cycle. According to the HI, the three locations present a warm temperate viticultural climate. However, the CI values describes important differences between the ripening periods observed during the summer and winter seasons. As can be noted (Table 3) the CI average values obtained from the three locations indicate a viticultural climate with "warm nights" for the summer season and a viticultural climate with "cool nights" (Campinas) and "very cool nights" (Monte Alegre do Sul and Jundiaí) for the winter season.

Before evaluating the results obtained from the trends tests, it has to be emphasized that the term "trend" may be regarded as a general direction to which the time series systematically moves (Weng, 2010). Thus, (for e.g.) consider the minimum air temperature series. A significant and positive

Table 3. Averages values of maximum (Tmax) and minimum (Tmin) air temperature series, rainfall series (Pre), Heliothermal index (HI), Growing Degree Days (GDD) and Cool night index (CI) series obtained from three locations of the State of São Paulo, Brazil

	Summer growing season (August-January)					Ripening (December-January)			
	Tmax	Tmin	Pre	HI	GDD	Tmax	Tmin	Pre	CI
Monte Alegre	27.7	15.4	910	2696	2129	28.3	17.4	510	18.1
Campinas	28.3	16.6	817	2836	2298	29.1	18.8	467	19.1
Jundiaí	27.9	15.2	842	2721	2128	29.3	17.6	466	18.0
	Winter growing season (January-June)					**Ripening (May-June)**			
	Tmax	**Tmin**	**Pre**	**HI**	**GDD**	**Tmax**	**Tmin**	**Pre**	**CI**
Monte Alegre	26.9	15.2	858	2529	2000	24.3	11.5	116	10.7
Campinas	27.6	16.6	785	2684	2187	24.8	13.1	110	12.4
Jundiaí	27.7	15.3	791	2653	2088	24.6	11.6	122	10.9

MK result indicates that the Tmin series are systematically moving to a warmer condition. Moreover, according to Blain (2013) and Danneberg (2012), if the outcomes obtained from the original MK and MK-PW test do not significantly differ from each other it may be assumed that there is no significant serial correlation affecting the trend analysis.

The results of the trend analyses obtained from the MK and MK-PW did not significantly differ from each other. In other words, the original MK and its modified form have led to equivalent conclusions regarding the presence of trends in all evaluated series. Thus, we assumed the presence of no significant autocorrelation affecting the trend analysis. Accordingly, the original Mann-Kendall test was used to evaluate the significance of the trends in both meteorological (Table 4) and agrometeorological series (Table 5).

Before evaluating the results presented in table 4, it is worth mentioning that meteorological evidences of warming trends have already been evaluated in several parts of South America. Vincent et al. (2005) evaluated the presence of trends in several indices of daily air temperature for South America. The results found by these authors indicate no consistent trends in the indices based on daily Tmax series while significant trends were found in the indices based on daily Tmin series. Based on several weather stations of the state of São Paulo, Blain (2011) also observed significant increasing trends in the Tmin series and no consistent trends in the Tmax series. These findings agree with the results of this study. The MK test indicates the presence of significant increasing trends in all Tmin series (Table 4). Based on the findings of Vincent et al. (2005) we may state that the

Table 4. Mann-Kendall test (MK) and Theil Sen Slope (Slope) applied to maximum (Tmax) and minimum (Tmin) air temperature series, rainfall series (Pre) and Diurnal Temperature Range (DTR) series obtained from three locations of the State of São Paulo, Brazil

		Summer growing season (August-January)					Ripening (December-January)				
		Tmax	Tmin	Tmed	Pre	DTR	Tmax	Tmin	Tmed	Pre	DTR
Campinas	Slope	n.s.	0.02	0.01	n.s.	-0.02	n.s.	0.02	0.01	n.s.	-0.02
	MK	0.23	6.33*	2.96*	1.01	-4.89	-0.6	4.98*	2.08*	0.74	-3.74
	p-value	0.82	<0.01	<0.01	0.31	<0.01	0.55	<0.01	0.04	0.46	<0.01
Monte Alegre do Sul	Slope	n.s.	0.02	0.01	n.s.	-0.01	n.s.	0.02	0.01	n.s.	-0.02
	MK	1.41	3.81*	3.43*	1.31	-2.14	1.74	3.95*	2.85*	0.97	-3.00
	p-value	0.16	<0.01	<0.01	0.19	0.03	0.08	<0.01	<0.01	0.33	<0.01
Jundiaí	Slope	n.s.	0.03	n.s.	n.s.	-0.05	n.s.	0.02	n.s.	n.s.	-0.05
	MK	-1.26	3.56*	1.65	0.96	-4.34	-1.77	2.75*	0.24	1.6	-3.20
	p-value	0.21	<0.01	0.1	0.34	<0.01	0.08	0.01	0.81	0.11	<0.01
		Winter growing season (January-June)					Ripening (May-June)				
		Tmax	Tmin	Tmed	Pre	DTR	Tmax	Tmin	Tmed	Pre	DTR
Campinas	Slope	n.s.	0.02	0.01	n.s.	-0.02	n.s.	0.02	n.s.	n.s.	-0.02
	MK	0.37	5.09*	3.21*	0.63	-4.16	-1.2	2.71*	0.81	1.61	-3.62
	p-value	0.71	<0.01	<0.01	0.53	<0.01	0.23	0.01	0.42	0.11	<0.01
Monte Alegre do Sul	Slope	0.01	0.02	0.01	n.s.	-0.01	n.s.	0.02	n.s.	n.s.	n.s.
	MK	2.37*	3.91*	3.44*	0.73	-1.6	-0.99	2.17*	0.78	0.35	-0.53
	p-value	0.02	<0.01	<0.01	0.46	0.11	0.32	0.03	0.44	0.73	0.63
Jundiaí	Slope	-0.02	0.03	n.s.	n.s.	-0.03	-0.03	0.03	n.s.	n.s.	-0.03
	MK	-2.86*	2.77*	-0.22	1.56	-2.68	-2.45*	1.96*	-0.33	-0.25	-2.61
	p-value	<0.01	0.01	0.83	0.12	<0.01	0.01	0.05	0.74	0.8	<0.01

n.s.non significant. * significant at the 5% level.

Table 5. Mann-Kendall test (MK) applied to Heliothermal index (HI), Growing Degree Days (GDD) and Cool night index (CI) series obtained from three locations of the State of São Paulo, Brazil

	August-January			January-June		
	HI	CI	GDD	HI	CI	GDD
			Campinas			
MK	1.20	2.63	3.03	1.65	2.58	3.08
p-value	0.23	0.01	<0.01	0.10	0.01	<0.01
			Monte Alegre do Sul			
MK	2.24	2.83	3.48	2.75	1.69	3.30
p-value	0.03	<0.01	<0.01	0.01	0.09	<0.01
			Jundiaí			
MK	-0.12	2.11	1.00	-1.42	2.10	-0.74
p-value	0.91	0.04	0.32	0.16	0.04	0.46

detected trends observed in the three locations are spatially consistent. As can be noted, the three Tmin series show a similar increasing pattern with a rate of change (slope) ranging from 0.02 to 0.03 °C.year^{-1}. In other words, the TSA values revealed a general warming trend raging from 1 to 1.5 °C over the last 50 years. This feature, observed in the three locations of the State of São Paulo, is consistent with those found by Jones et al. (2005). As previously described, several world high quality wine-producing regions experienced growing season warning trends of, approximately, 1.3 °C during the years of 1950 to 1999.

The above-mentioned results allow us to infer that the significant increasing trends detected in the average monthly air temperature series (Tmed; Table 3) are fundamentally driven by the increase in the minimum air temperature series. This last inference agrees with the results found by Back et al. (2012) for the Goette Valley-SC and by Blain (2011) for several weather stations of State of São Paulo. As observed for the Tmax series, the MK test indicates the presence of no significant trend in the PRE series. This result agrees with previous studies carried out in the State of São Paulo (Blain, 2010; 2012) that also indicate a lack of a general temporal change in the monthly rainfall series of the State of São Paulo. Naturally, the significant increasing trends detected in the Tmin series along with the lack of significant trends observed in the Tmax series have led to significant decreasing trends in virtually all diurnal temperature range series (DTR).

Regarding the question posed at the beginning of this study, one may infer that the significant trends detected in the Tmin and DTR series (Table 4) support the hypothesis of the presence of climate change that may affect the wine production of the eastern part of the State of São Paulo (Falcão et al., 2010; Giovaninni and Manfroi, 2009). This hypothesis is also consistent with the results presented in table 5. As can be noted, 11 out of the 18 agrometeorological series show significant warming trends. In particular, 5 out of the 6 CI series show significant increasing trends. By following Tonietto and Carbonneau (2004) and Tonietto et al. (2006), we may indicate that these significant increasing trends obtained from the CI series may be regarded as an unfavorable change in the regional climate conditions related to wine color and aroma. This change to warmer nights may also be regarded as an unfavorable effect of the detected climate trends because, during grape ripening, cool night temperatures favor the sugar accumulation and limit the vegetative growth (Falcão et al., 2010; Rosier, 2006). Finally, the long-term average rates of change of the CI values (Figure 1) vary from 0.01 °C.year^{-1} to 0.04 °C.year^{-1}. These TSA values are similar to those found by Back et al. (2012; 2013) for, respectively, the regions of the Goethe Grape Valleys and Vale do Rio Peixe (≈0.03 °C.year^{-1}).

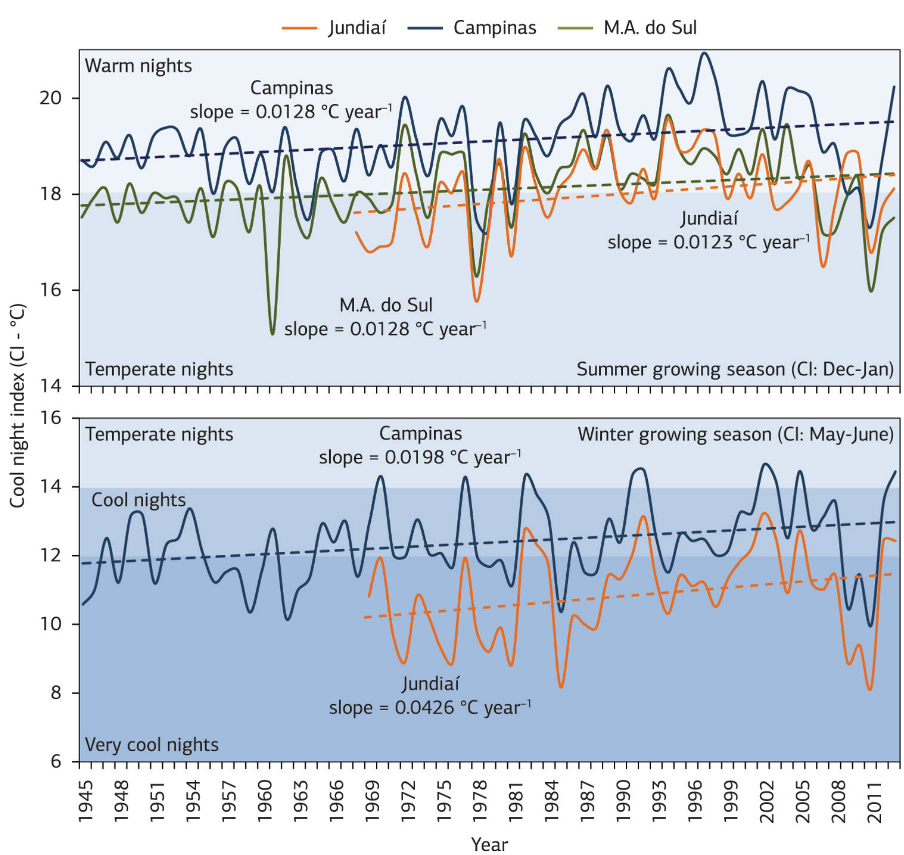

Figure 1. Temporal variability of the Cool night index observed in different locations of the State São Paulo. The dashed line represents the long-term rate of change per time unit (year).

Before analyzing the GDD and HI series (Table 5), it is worth recalling that these two indices are used in viticulture to quantify the temperature availability in a specific area (Orlandini et al., 2009). Therefore, the significant increasing trends detected in GDD (Campinas and Monte Alegre do Sul) and in the HI series (Monte Alegre do Sul), indicate a shortening in the grapevine phenological phases. These latter results are similar to those found by Back et al. (2012; 2013), Orlandini et al. (2009), Ramos et al. (2008) and Tomasi et al. (2011), for several grapevine-producing regions of the world. Finally, after analyzing equations 1 and 2, one may correctly argue that the HI is less sensitive than the GDD to changes in Tmin series because it gives more weight to Tmax data (Anderson et al., 2012, Hall and Jones, 2010; Tomasi et al., 2011). This latter feature and the different rate of changes shown by the Tmax and Tmin series (Table 4) explain the lower number of HI series showing significant increasing trends (Table 5). Only 2 out of the 6 HI series show significant increasing trends (Monte Alegre do Sul).

The results depicted in figure 2 indicate that the GDD series of Campinas has been subjected to a long-term warming of, approximately, 1.96 $GDD.year^{-1}$ (summer season) and 1.91 $GDD.year^{-1}$ (winter season). A similar pattern is also observed for the GDD series of Monte Alegre do Sul which has been subjected to a warming of, approximately, 1.66 $GDD.year^{-1}$ (summer season) and 2.23 $GDD.year^{-1}$ (winter season). These four TSA values are lower than those found by Back et al. (2012) in the Goethe Valley (5.2 $GDD.year^{-1}$) and by Back et al. (2013) for the Vale do Rio Peixe-SC (8.82 $GDD.year^{-1}$). The TSA values obtained from the HI series of Monte Alegre do Sul (Figure 3) indicate that the detected trends have slopes of, approximately, 1.19 $HI.year^{-1}$ (summer season) and 1.73 $HI.year^{-1}$ (winter season). These two TSA values are lower than those found in other vine-producing regions of the World (Back et al., 2013; Jones et al., 2005; Ramos et al., 2008) that have been subjected to significant trends in both Tmax and Tmin series. On the other hand, these two TSA values (Figure 3) are similar to those found by Back et al. (2012) for the Goetty Valley – SC (1.85 $HI.year^{-1}$). At this point, it becomes worth recalling that this latter study also detected no significant trend in the Tmax series.

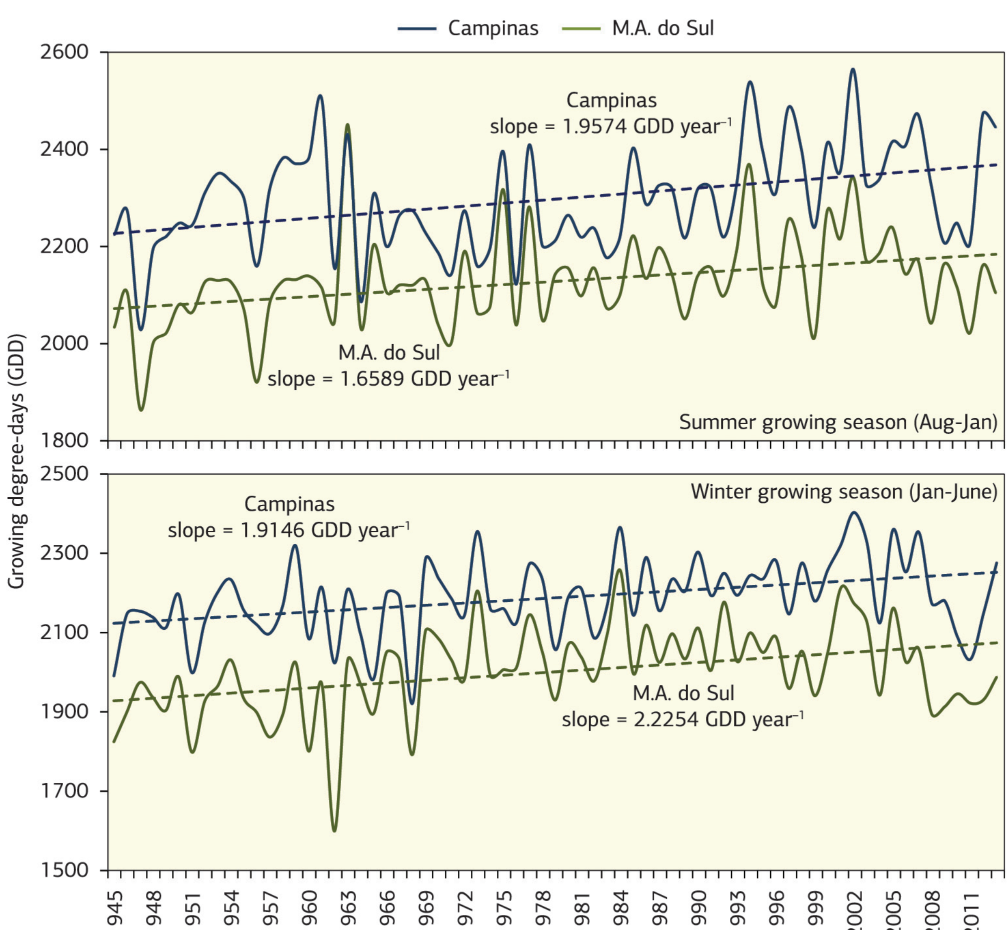

Figure 2. Temporal variability of the Growing Degree Days observed in different locations of the State São Paulo. The dashed line represents the long-term rate of change per time unit (year).

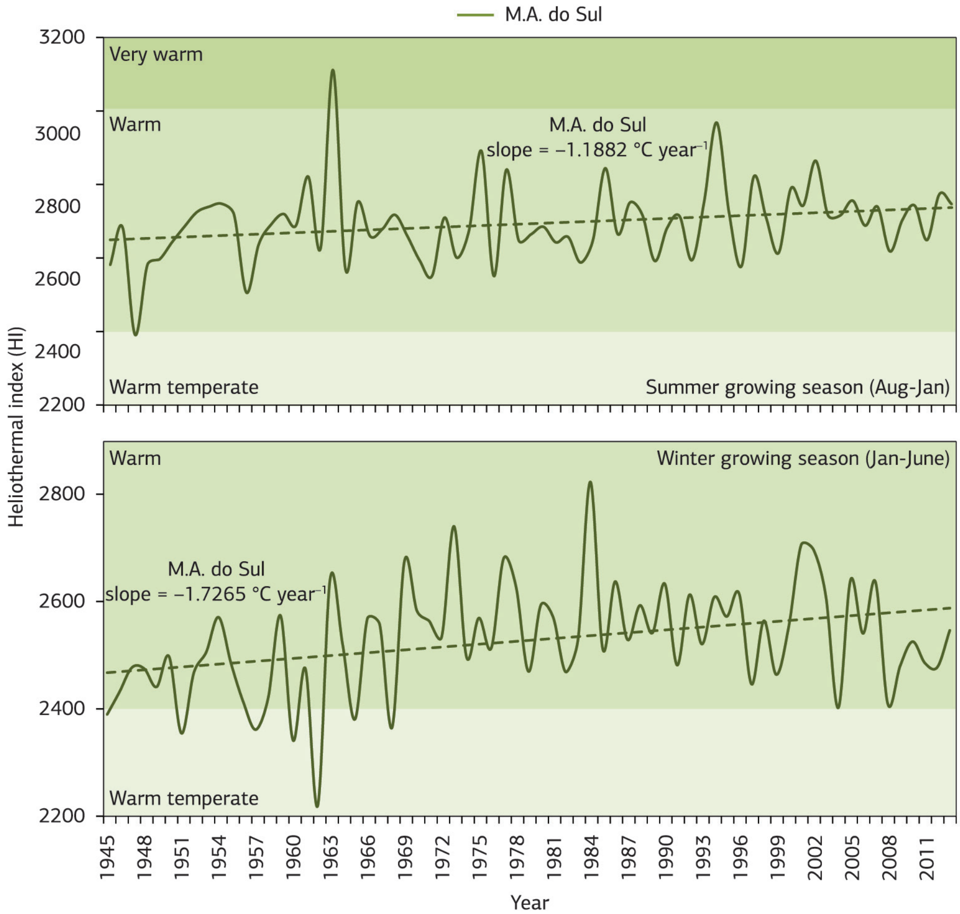

Figure 3. Temporal variability of the Heliothermal index observed in different locations of the State São Paulo. The dashed line represents the long-term rate of change per time unit (year).

4. CONCLUSION

The results found in this study support the hypothesis of the presence of climate trends in the wine producing region of the eastern part of the State of São Paulo-Brazil. These trends are mostly linked to changes in the minimum air temperature. The results also reveal a shortening in the duration of grapevines phenological phases and a change to warmer conditions during the ripening Months. These changes are consistent with the climate changes observed in virtually all traditional wine producing regions of the world and may negatively affect the wine production of the eastern part of the State of São Paulo.

ACKNOWLEDGEMENTS

Ludmila Bardin-Camparotto acknowledges the Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) for a post-doctorate scholarship. Mário José Pedro Júnior acknowledges the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for a research productivity fellowship.

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