IMPACT OF CLIMATE CHANGE ON SOME GRAPEVINE VARIETIES GROWN IN PERU FOR PISCO PRODUCTION

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Abstract

Aim : The Peruvian region of Ica is an important area of grapevine cultivation, mainly for the production of pisco, the flagship hard drink of Peru. The effects of a changing climate have been assessed using the recorded temperatures of a weather station together with projected climates for the 21st century generated under the A1B SRES scenario.

Methods and results : The bioclimatic indices commonly used in grapevine studies have increased in recent years and will continue to rise along the 21st century in relation to increasing temperature. In parallel, the phenology of four pisco cultivars (Quebranta, Torontel, Moscatel and Italia) has been experimentally assessed during four consecutive years, first to determine their cumulative growing degree-days and then to project them in past and future climates.

Conclusion : It appears that the cycle lengths of these cultivars have been shortened in recent years and that this tendency will continue all along the 21st century.

Significance and impact of the study : Assessing the immediate and future impact of climate change makes it possible to identify potential crop production problems and provides information on adaptation strategies.

Key words : *Vitis vinifera*, pisco cultivars, Peru, climate change

Résumé

Objectif : La région d'Ica au Pérou est une zone viticole importante, principalement pour la production de pisco, l'alcool phare du pays. Les effets du changement climatique ont été analysés en utilisant les températures d'une station météorologique ainsi que les températures simulées pour le XXIe siècle avec le scénario SRES A1B.

Méthodes et résultats : Les indices bioclimatiques classiquement utilisés dans les études viticoles ont tous augmenté au cours des dernières années et continueront à le faire au cours du XXIe siècle en relation avec une température croissante. Parallèlement, la phénologie de quatre cultivars utilisés pour la production de pisco (Quebranta, Torontel, Moscatel et Italia) a été étudiée expérimentalement durant quatre années consécutives, d'abord pour déterminer leurs sommes de température (degrés-jours) et ensuite pour les projeter dans les climats passés et futurs.

Conclusion : Il s'avère que les cycles de ces cultivars se sont raccourcis au cours des dernières années et que cette tendance continuera tout au long du XXIe siècle.

Signification et impact de l'étude : L'étude des effets du changement climatique dans un avenir immédiat et lointain permet d'identifier d'éventuels problèmes de culture et fournit des renseignements sur les stratégies d'adaptation.

Mots clés : *Vitis vinifera*, cultivars à pisco, Pérou, changement climatique

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INTRODUCTION

Since global warming is a fact universally recognized all over the world (IPCC, 2007), it is important to assess its current and future effects on both natural and agricultural ecosystems, given that temperature has a strong impact on plant phenology. Many studies have been carried out in different regions of the world concerning the effects of a changing climate on viticulture and wine quality and the impact of past and future changes in temperature on grapevine phenology. Jones and Davis (2000) noted that over the last two decades of the 20th century, in Bordeaux, the phenological events of grapevines tended to occur earlier over a longer growing season. Tomasi *et al.* (2011) studied several cultivars in relation with climate change in the Veneto region of Italy and found an early shift of 13 to 19 days for the main phenological events. Webb *et al.* (2012) indicate that in Australia, wine grape ripening has advanced in recent years and that warming and declines in soil water content are driving a major portion of this ripening trend. On the basis of modelled impact of future climate change in Australia, Webb *et al.* (2007) indicate that the period between budburst and harvest for Chardonnay and Cabernet-Sauvignon cultivars will be reduced by 37 to 40 days. Jorquera-Fontena and Orrego-Verdugo (2010) showed that in Chile the temperature increase projected for the 2070-2100 period with the A2 and B2 scenarios will reduce by 28 to 46 days the period from budburst to harvest of the Gewürztraminer cultivar. Using climate projections, Ruml *et al.* (2012) showed that the viticultural areas of Serbia will tend to become warmer and dryer by the end of the 21st century. These studies, and other studies not cited here, clearly demonstrate that climate change will have multiple impacts on a viticultural region: changes in the chemical composition and organoleptic characteristics of grapes and wines, phenological changes modifying the ripening date, changes in crop water requirements, changes in pest and diseases, and changes in the cultivars used in a specific region, all these impacts having significant consequences on the socio-economic environment.

In Peru, grapevine cropping is an important economic activity, either for the production and export of early table grapes or for wine and pisco production. In this study, we assess the impacts of climate change on some grapevine cultivars grown in the Peruvian region of Ica to produce pisco. Pisco is a colourless grape brandy considered as the flagship of Peru (Huertas Vallejos, 2004): about 6.3 million litres of pisco were produced in 2011 and 7.1 million in 2012, with about 8 % for export. Using past climatic data and future data generated by an Atmospheric General Circulation Model, the impacts of climate change are assessed in order to identify possible production problems and provide information on adaptation strategies. This assessment is made first through the climatic indices commonly used in grape-related studies to identify and compare viticulture climates worldwide (Tonietto and Carbonneau, 2004), then through the phenology of these specific cultivars projected in past and future climates, their thermal time requirements having been previously determined by an experiment conducted in situ.

MATERIALS AND METHODS

1. Study area and cultivars

Pisco is obtained by distillation of recently fermented must from specific grapevine varieties (*Vitis vinifera*). These "pisco" varieties are mainly grown in the coastal areas of several Peruvian departments (administrative districts): Lima, Ica, Arequipa, Moquegua and also in some valleys of Tacna. The main production area, however, is the department of Ica, located in the desert, central coast of Peru (Figure). Its climate is typically arid. The average daily sunshine duration is 7 hours, and the average temperature is 21 °C with a maximum mean of 29 °C and a minimum mean of 14 °C (Abreu and Bannon, 1993). As the annual precipitation is almost zero (the long term amount is 2 mm), vineyards are irrigated either by surface (flood) systems, with water mainly coming from the Ica River, or by drip systems with subterranean water.

Four cultivars, commonly grown in the region for pisco production, were investigated: Quebranta, Italia, Torontel and Moscatel (Caceres, 2012). Quebranta has a Peruvian origin and is the result of hybridization between two cultivars: Negra Criolla from Spain and Negra Mole from Portugal. With an herbaceous flavour, it is used to elaborate non-aromatic piscos. Italia is a cultivar originated from Turkey, called "Italia" in Peru, but internationally known as "Muscat of Alexandria". Extensively grown in Spain (Malaga and Valencia), it is very aromatic and has a high content in sugar. It is used as table grape and to elaborate wine. Torontel is an aromatic cultivar belonging to the Muscat family. It produces elegant and structured piscos and it is used in France to elaborate the "Muscat de Frontignan". Moscatel also belongs to the Muscat family. Sometimes called "Muscat de Roussé", it is used for refined, aromatic piscos. Further details on these cultivars can be found in the *Vitis* international variety catalogue (www.vivc.de/).

2. Past and future climate data

The study is based on temperature data recorded at the weather station of San Camilo (lat. 14° 04' 24", long. 75° 42' 40", alt. 398 m), which is well located in the centre of the Ica region, far enough from the coastal line (Figure 1). It has also the longest records of temperature data: 54 years (1960-2013). Future climate data were generated by the Atmospheric General Circulation model MRI/JMA TL959L60 of the Japanese Meteorological Agency (Noda *et al.*, 2008), which was validated with 20 stations of the coastal region of Peru. MRI simulations for the present days and future climates are performed by using the observed sea surface temperatures (SST) and their changes projected by atmosphere-ocean coupled models as the lower boundary conditions. With a 20-km grid, they reproduce fairly well the features of the general circulation in Peru, the climate trends, the seasonal cycle and the mean meteorological variables (Blázquez and Nuñez, 2013). They exhibit, however, some bias, underestimating minimum temperatures (average bias around 3 °C) and slightly overestimating maximum temperatures (around 1.6 °C), but these bias are coherent with the results of the Coupled Models Inter-comparison Project (Phase 5) (IPCC, 2013). The MRI model also correctly represents the influence of El Niño (1982-1983 and 1997-1998). The future climate was run under the SRES scenario A1B of the IPCC, which constitutes a good mid-line for CO_2 emission and economic growth (CO_2 emission increases until 2050 and then decreases). Two periods of 25 years were considered: the immediate future (2015-2039) and the distant future (2075-2099). Given that systematic errors preclude the direct use of climate model outputs, future data were obtained on a daily basis using the "climate anomalies" method (Déqué, 2007; Wilby *et al.*, 2009). Additive or multiplicative change factors, calculated on a monthly basis, were applied to the observed daily weather data to generate the future data, as detailed in Lhomme *et al.* (2009).

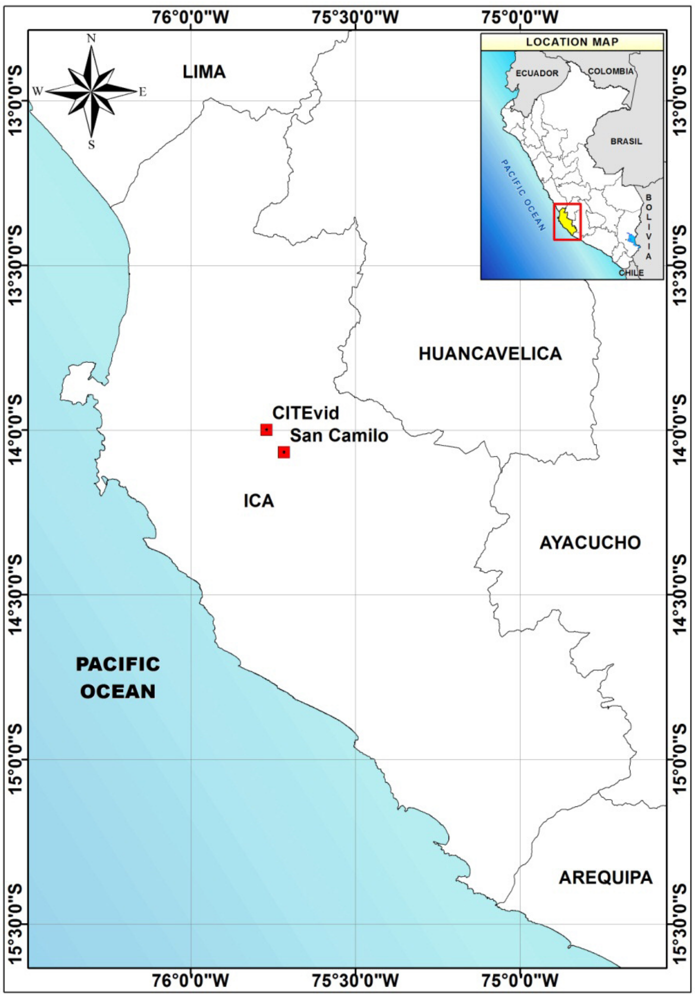

Figure 1 – Study area: department of Ica in southwestern Peru, with the location of the San Camilo weather station and the CITEvid.

3. Bioclimatic indices

Four bioclimatic indices commonly used in grapevine-related studies (Tonietto and Carbonneau, 2004; Hall and Jones, 2010; Montes *et al.*, 2012) are determined: the average Growing Season Temperature (GST), the Growing Degree-Days Index (GDDI), the Huglin's Heliothermal Index (HI) and the Cool Night Index (CNI). They are calculated over the entire growing season, from October to April, as described below, except the HI which is calculated from October to March. They involve the maximum daily temperature ($T_{d,x}$), the minimum daily temperature ($T_{d,n}$) or the mean daily temperature ($T_{d,m}$). The average GST is the simplest of the four and represents the average daily temperature of the growing season, from October 1 to April 30:

$$GST = \left[\sum_{d=oct\ 1}^{d=April\ 30} \left(\frac{T_{d,x} + T_{d,n}}{2} \right) \right] / 212$$

The range between 13 °C and 24 °C is generally considered to be suitable for wine grape production

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(Hall and Jones, 2010). GDDI, also called Winkler index (WI), is expressed as:

$$GDDI = \sum_{d=Oct\ 1}^{d=Apr\ 30} \max\left[\frac{T_{d,x} + T_{d,n}}{2} - 10{,}0\right]$$

Calculated over the same period as GST, from October to April, it indicates the suitability of growing grapevine in a given environment (Winkler *et al*., 1974). HI provides information on sugar potential and thus on grape quality (Huglin, 1978):

$$HI = \sum_{d=Oct\ 1}^{d=Mar\ 31} \max\left[\frac{T_{d,m} - 10 + T_{d,x} - 10}{2}, 0\right] K$$

K is an adjustment coefficient for day length with the value of 1 for low latitudes (< 40°). Generally, this index is calculated on one month less than the other indices. It is maintained here in this form for ease of comparison with published data (Jones *et al*., 2010). CNI accounts for the average minimum night temperature of the month when ripening usually occurs, here in March:

$$CNI = \left[\sum_{d=Mar\ 1}^{d=Mar\ 31} T_{d,n}\right] /31$$

This index has some relevance in relation with grape and wine colour and aroma (Tonietto and Carbonneau, 2004).

4. Growing degree-days experiment

The experiment took place in the "Centro de Innovacion Tecnologica Vitivinicola" (CITEvid), situated close to the town of Ica (lat. South 13° 59' 57", long. West 75° 46' 13", alt. 427 m). The grapevines were planted in 2002 and grafted on different rootstocks (Paulsen 1103 for Quebranta and Italia, MGT-101-14 for Moscatel and Torontel). The training system was overhead trellis (espalier) with a distance of 3 m between rows and 2 m between two plants within the same row. The soil was a sandy loam with low organic matter content. Drip irrigation was used at about 1,100 $m^3\ ha^{-1}$ (i.e., 1100 mm) for each crop cycle. During four agricultural years, from 2010 to 2014, 10 plants were monitored every week from pruning to harvest for each of the four grapevine cultivars considered in the study.

It is universally accepted that plant phenological development is regulated by temperature. The simplest approach is to consider that plant growth and development are proportional to thermal time, defined as the sum of the daily average temperatures between a lower and an upper temperature threshold. This type of model is commonly used in plant phenology studies and particularly in those related to grapevine (Moncur *et al*., 1989; Oliveira, 1998). More complex phenological models, however, were developed and tested (Parker *et al*., 2011). In our study, growing degree-days (GDD) were calculated from the standard equation where average air temperature is defined as the mean between daily maximum ($T_{d,x}$) and minimum ($T_{d,n}$) air temperature above a threshold (T_b) of 10 °C:

$$GDD = (T_{d,x} + T_{d,n})/2 - T_b$$

If $(T_{d,x}+T_{d,n})/2 < T_b$, then GDD = 0. This equation corresponds to the method 1 described by McMaster and Wilhelm (1997) and seems to be the most widespread method in simulation models. It is assumed that the requirement of GDD is approximately constant for the completion of a given developmental phase.

The chilling period generally needed to stop the dormancy in temperate regions does not occur in the tropical region of Ica. In this context, the growing cycle is assumed to begin three days after pruning, usually in August, when cyanamide is applied to release grapevine buds from dormancy. Four phenological intervals were retained and defined from three major events observed on the stem of the year: budburst (green tip), full flowering and veraison, each event being observed on 50 % of plants. Phase I is from pruning to budburst; phase II from budburst to full flowering; phase III from full flowering to veraison; and phase IV from veraison to harvest (Coombe, 1988; Coombe, 1995). These major events have the following codes on the BBCH scale (Lorenz *et al*., 1994): green tip (09), full flowering (65), veraison (83) and ripe berries (89). Harvest date was determined when grape sugar content reached 24 degrees Brix, which corresponds to a good trade-off between sugar concentration and acidity. Budburst was observed on two spurs (branches) of the previous year, each one bearing 3 to 4 buds left after pruning. For the sake of convenience, in the rest of the paper the so-called "pruning date" corresponds to the date when cyanamide is applied, i.e., three days after pruning.

RESULTS

1. Behaviour of temperature and bioclimatic indices

Figure 2 shows the time variation of yearly mean, maximum and minimum temperatures during the

Table 1 − Mean values of the bioclimatic indices in the reference period and future climates. The number in parentheses represents the percentage of increase compared to the reference period.

Period	HI (°C)	GDDI (°C)	GST (°C)	CNI (°C)
Reference period (1960-2013)	3105	2823	23.3	17.6
Immediate future (2015-2039)	3191 (+3 %)	2891 (+2 %)	23.6 (+1 %)	17.6 (0 %)
Distant future (2075-2099)	3581 (+15 %)	3391 (+20 %)	26.0 (+12 %)	20.3 (+15 %)

HI: Huglin's heliothermal index, GDDI: growing degree-days index, GST: growing season temperature, CNI: cool night index.

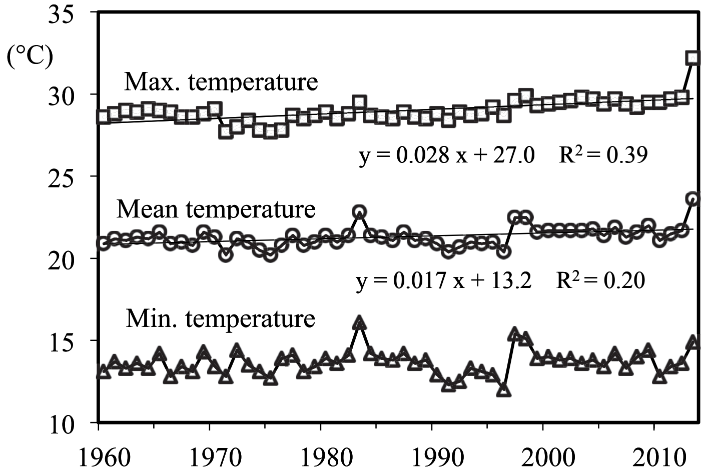

Figure 2 − Time course of mean annual temperatures during the reference period (1960-2013).

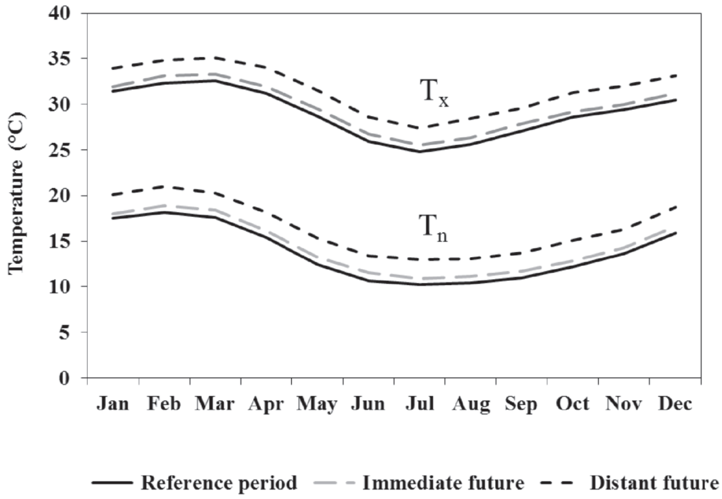

Figure 3 − Annual variation of mean monthly temperature (T_x: maximum, T_n: minimum) during the reference period and the future climates (immediate and distant) as simulated by the General Circulation Model.

reference period (1960-2013). There is a slight increasing trend over the entire period, statistically significant for maximum and mean temperatures, the increase being more marked from 1995 up to now. The increase in minimum temperature is less clear and not statistically significant. The years when the El Niño (ENSO) phenomenon occurs (1982-1983 and 1997-1998) are characterized by an increase of air temperature, which translates into a net increase of the bioclimatic indices. Figure 3 shows how the annual cycles of maximum and minimum air temperature, as simulated by the MRI model, change in the future periods in comparison with the reference period. Temperature systematically increases in the future periods all year round. However, the increase is stronger between immediate and distant future (about 2 °C) than between the reference period and immediate future (less than 1 °C). Table 1 shows the average values of the bioclimatic indices for the future projections in comparison with the reference period. All the indices increase in the future climates (immediate and distant), but the increase is stronger for the distant future: for instance, HI increases by about 3 % in the immediate future and by 15 % in the distant future compared with the reference period.

2. Determination of growing degree-days

The results of the experiment on grapevine phenology conducted during four consecutive years are shown in Table 2 in terms of days and degree-days. For the four grapevine cultivars used for pisco elaboration, the average number of days needed to complete the entire cycle (from pruning to harvest) is relatively stable, around 204 days, with a little more for Italia and a little less for Moscatel. There is, however, an observable variation between years: the standard deviation varies from 5 days for Torontel to 9 days for Italia. The average value of the cumulative thermal time corresponding to the entire cycle is very similar for the four grapevine varieties, circa 2630 degree-day, with a coefficient of variation (ratio of standard deviation to mean) around 6 %. It is worthwhile noting that the cultivars grown for table grapes in the same area, such as Superior Seedless or Flame Seedless, have shorter vegetative cycles than those used for pisco production (results not shown). Indeed, they are harvested earlier, given that they require lower sugar content than pisco cultivars. They also present more variable results owing to management practices related to market demands.

3. Past and future trend in grapevine phenology

The cycle length of each variety has been simulated for each year of the reference period and the future climates using the cumulative GDD (mean value) determined above and setting arbitrarily the pruning date on August 15, given that this event usually occurs in mid-August. This exercise is based upon the assumption that the GDD model, as determined in the experiment, is a plant characteristic transferable from one year to another. The results concerning the past climate (1960-2013) are shown in Figure 4 for two representative varieties (Italia and Moscatel), very similar results being obtained for the other two varieties. There is a slight decreasing trend of the crop cycle length, which is statistically significant ($p < 0.05$) for the four varieties, with a slope of about -0.16, which means a decrease of about 1.6 days every ten years. In the future climates, the cycle length is systematically reduced, compared to the reference period (1979-2004). The results are shown in Figure 5 for the Moscatel and Italia varieties. The reduction is almost the same for the four varieties: the growing cycle length decreases from almost 220 days in the reference period to about 185 days in the distant future. And as could be anticipated, the reduction is greater in the distant future than in the immediate future.

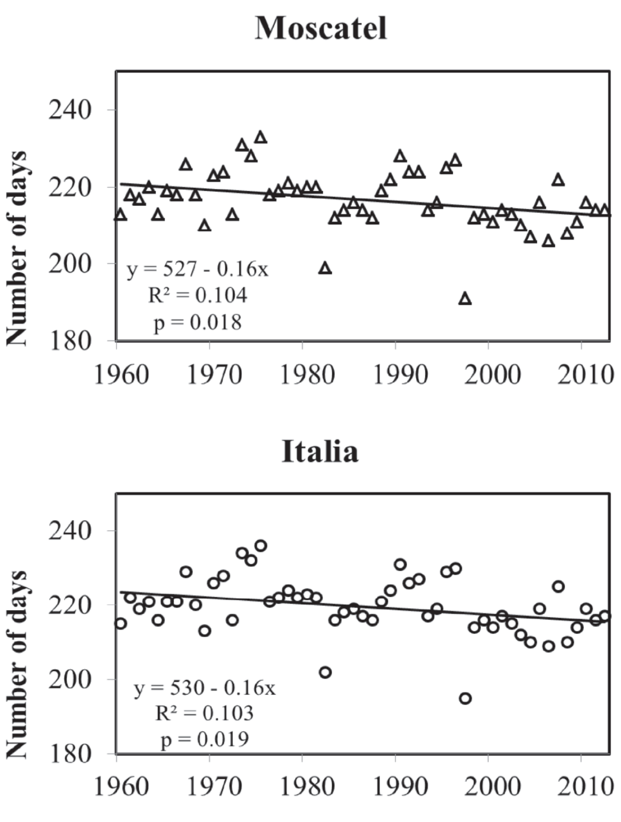

Figure 4 − Time variation of growing cycle length during the 1960-2013 period for Moscatel and Italia varieties.

DISCUSSION

The bioclimatic indices used in the study should be calculated over similar calendar periods in each hemisphere in order to be comparable, and they should correspond approximately to the mean development cycle of the grapevine. They have been applied by Tonietto and Carbonneau (2004) to identify and compare viticultural regions all over the world, their sample providing an extensive geographic distribution with latitudes between 4° and 51° in the Northern Hemisphere and between 6° and 45° in the Southern Hemisphere. According to the classification based on the heliothermal index (Tonietto and Carbonneau, 2004), the climate of Ica is a very hot viticultural climate (HI +3), HI being systematically greater than 3000. Following the classification of Jones *et al.* (2010), based upon GDDI and HI indices, the climate of the region is "too hot" for the reference period as well as for the future climates (GDDI > 2700 and HI > 3000). The higher temperatures predicted by the climate model will systematically shorten the growing cycles. Higher temperatures during the maturation stage will also increase grape sugar content and decrease acidity. For pisco production it is important to keep in mind that the degrees Brix should not be greater than 25, because above this threshold, grape begins a process of dehydration with less acidity and loss of aromas.

With higher temperatures, crop evapotranspiration will be enhanced. Consequently, crop water requirements and irrigation frequency will increase. Water availability certainly remains the most critical issue in the region given that all the vineyards are irrigated (about 70 % by flood systems and the rest by drip irrigation). Higher water demand could also have severe consequences with respect to pest control. Most winegrowers in the region of Ica use non-grafted plants which are not resistant (but only tolerant) to Phylloxera. Flood irrigation allows the root form of Phylloxera

Table 2 − Growing degree-days and number of days corresponding to the different phenological intervals of the four cultivars (SD : standard deviation, CV : coefficient of variation).

Cultivar	Growing season	Pruning date	Pruning-Green Tip		Green Tip- Flowering		Flowering-Veraison		Veraison-Harvest		Pruning-Harvest	
			Degree-days	Days	Degree-days	Days	Degree-days	Days	Degree-days	Days	Degree-days	Days
Quebranta	2010-11	29 Aug.	213	22	543	51	844	63	1140	70	2740	206
	2011-12	07 Sep.	224	22	561	51	909	63	1137	66	2832	202
	2012-13	12 Aug.	197	22	498	51	699	62	1160	78	2554	213
	2013-14	05 Sep.	210	23	478	50	808	63	894	60	2390	196
	Mean		**211**	**22**	**520**	**51**	**815**	**63**	**1083**	**69**	**2629**	**204**
	SD		11	0.5	39	0.5	88	0.5	126	7.5	197	7.1
	CV (%)		5	2.2	7	1.0	11	0.8	12	11.0	7	3.5
Torontel	2010-11	27 Aug.	225	23	540	51	844	63	1062	65	2671	202
	2011-12	04 Sep.	234	23	557	51	910	63	1123	65	2823	202
	2012-13	16 Aug.	236	24	495	50	735	63	1133	75	2598	212
	2013-14	01 Sep.	222	24	468	49	816	64	978	65	2483	202
	Mean		**229**	**24**	**515**	**50**	**826**	**63**	**1074**	**68**	**2644**	**205**
	SD		7	0.6	41	1.0	73	0.5	71	5.0	142	5.0
	CV (%)		3	2.5	8	1.9	9	0.8	7	7.4	5	2.4
Moscatel	2010-11	28 Aug.	195	20	459	43	920	72	1084	66	2658	201
	2011-12	04 Sep.	221	22	434	41	1021	73	1123	65	2799	201
	2012-13	16 Aug.	221	23	397	40	816	72	1145	76	2578	211
	2013-14	06 Sep.	211	23	381	40	874	70	945	63	2410	196
	Mean		**212**	**22**	**418**	**41**	**908**	**72**	**1074**	**68**	**2611**	**202**
	SD		12	1.4	35	1.3	87	1.3	90	5.8	162	6.3
	CV (%)		6	6.4	8	3.1	10	1.8	8	8.6	6	3.1
Italia	2010-11	24 Aug.	188	20	523	49	905	70	1090	66	2705	205
	2011-12	04 Sep.	212	21	526	49	1011	70	1037	60	2785	200
	2012-13	16 Aug.	198	21	483	49	807	69	1203	80	2690	219
	2013-14	01 Sep.	184	20	469	50	881	70	901	60	2435	200
	Mean		**195**	**21**	**500**	**49**	**901**	**70**	**1058**	**67**	**2654**	**206**
	SD		12	0.6	29	0.5	84	0.5	125	9.4	152	9.0
	CV (%)		6	2.8	6	1.0	9	0.7	12	14.2	6	4.4

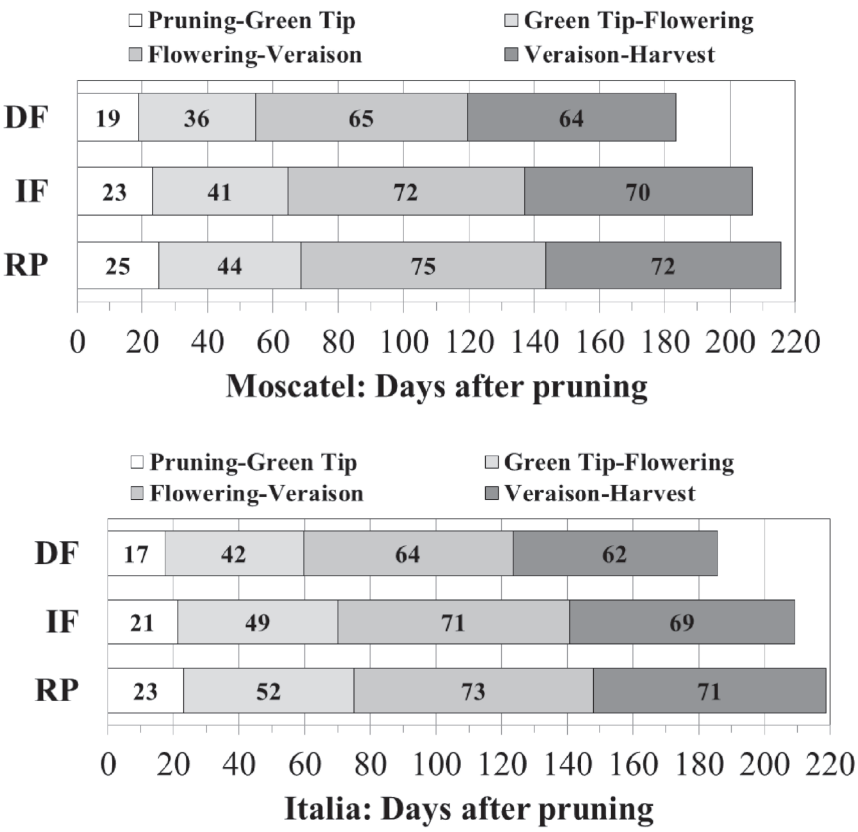

Figure 5 − Mean value of the cycle length and of its different phenological phases in the distant future (DF), the immediate future (IF) and the reference period (RP).

to be controlled, the pest being asphyxiated by a strong flow of water. If irrigation water should be saved by using drip systems instead of flood systems, the pest biological cycle will not be controlled, which will lead to lower yields. In this case, winegrowers might benefit from transforming their vineyards to grafted plants resistant to Phylloxera.

At tropical and subtropical latitudes, the Niño and Niña events constitute important features of the climatic system. El Niño is associated with air temperature warmer than normal and during La Niña episodes, opposite conditions prevail (Garreaud, 2009). These changes generate important climatic disturbances. Precipitations generally increase along the coastal areas of Ecuador and Peru during El Niño events (Vera and Silvestri, 2009). In the central coast of Peru during El Niño 1982-1983 and 1997-1998, the changes in minimum daily temperature, which are more significant than those in maximum temperature, reached up to 7 °C above the normal value at the San Camilo station (Ica), as shown in Figure 2. As a consequence, the green tip phase, which generally does not occur before August, occurred in June during El Niño 1997 and led to early harvest and low yields.

CONCLUSION

Temperature data recorded in the Peruvian region of Ica show that there has been a slight increase during the recent years, mainly for maximum temperature. Future climatic data generated under the SRES scenario A1B indicate that this increase will continue during the 21st century. Consequently, all the bioclimatic indices commonly used in grapevine studies (GST, GDDI, HI, CNI) have increased and will continue to rise. The phenology of four cultivars grown for pisco production was investigated during four consecutive years and the cumulative thermal times of their different phenological stages were determined. The entire cycle is completed within approximately 204 days, summing about 2630 degree-day for all the four grapevine varieties. From these results, it was inferred that during the recent years, cycle lengths have been shortened by about 2 days every ten years and that, according to the projected climate, the tendency will continue all along the 21st century.

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REFERENCES

Abreu M. and Bannon P., 1993. Dynamics of the South American coastal desert. *J. Atmos. Sci.*, **50**, 2952-2964.

Blázquez J. and Nuñez M.N., 2013. Performance of a high resolution global model over southern South America. *Int. J. Climatol.*, **33**, 904-919.

Cáceres H., 2012. *Catálogo Ampelográfico de Variedades de Uvas Pisqueras de la Denominación de Origen Pisco*. CITEvid, Ica, Perú.

Coombe B.G., 1988. Grapevine phenology. *In* : *Viticulture, volume I*. Australian Industrial Publishers, Adelaide, pp. 139-153.

Coombe B.G., 1995. Adoption of a system for identifying grapevine growth stages. *Aust. J. Grape Wine Res.*, **1**, 100-110.

Déqué M., 2007. Frequency of precipitation and temperature extremes over France in an anthropogenic scenario : model results and statistical correction according to observed values. *Glob. Planet. Change*, **57**, 16-26.

Garreaud R.D., 2009. The Andes climate and weather. *Adv. Geosci.*, **22**, 3-11.

Hall A. and Jones G.V., 2010. Spatial analysis of climate in winegrape-growing regions in Australia. Aust. *J. Grape Wine Res.*, **16**, 389-404.

Huertas Vallejos L., 2004. Historia de la producción de vinos y piscos en el Perú. *Rev. Universum*, **19**, 44-61.

Huglin P., 1978. Nouveau mode d'évaluation des possibilités héliothermiques d'un milieu viticole. *C.R. Acad. Agric. Fr.*, **64**, 1117-1126.

IPCC (Intergovernmental Panel on Climate Change), 2007. *Climate Change 2007: The Physical Science Basis. Climate Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Solomon S., Qin D., Manning M., Chen Z., Marquis M., Averyt K.B., Tignor M. and Miller H.L. (eds.), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2013. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker T.F., Qin D., Plattner G.K., Tignor M., Allen S.K., Boschung J., Nauels A., Xia Y., Bex V. and Midgley P.M. (eds.), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jones G.V. and Davis R.E., 2000. Climate influences on grapevine phenology, grape composition, and wine production and quality for Bordeaux, France. *Am. J. Enol. Vitic.*, **51**, 249-261.

Jones G.V., Duff A.A., Hall A. and Myers J.W., 2010. Spatial analysis of climate in winegrape growing regions in the Western United States. *Am. J. Enol. Vitic.*, **61**, 313-326.

Jorquera-Fontena E. and Orrego-Verdugo R., 2010. Impact of global warming on the phenology of a variety of grapevine grown in southern Chile. *Agrociencia*, **44**, 427-435.

Lhomme J.P., Mougou R. and Mansour M., 2009. Potential impact of climate change on durum wheat cropping in Tunisia. *Clim. Change*, **96**, 549-564.

Lorenz D.H., Eichhorn K.W., Blei-Holder H., Klose R., Meier U. and Weber E., 1994. Phänologische entwicklungsstadien der weinrebe (*Vitis vinifera* L. ssp. *vinifera*). *Vitic. Enol. Sci.*, **49**, 66-70.

McMaster G.S. and Wilhelm W.W., 1997. Growing degree-days : one equation, two interpretations. *Agric. Forest Meteorol.*, **87**, 291-300.

Moncur M.W., Rattigan K., Mackenzie D.H. and Mc Intyre G.N., 1989. Base temperatures for budbreak and leaf appearance of grapevines. *Am. J. Enol. Vitic.*, **40**, 21-26.

Montes C., Perez-Quezada J.F., Peña-Neira A. and Tonietto J., 2012. Climatic potential for viticulture in Central Chile. *Aust. J. Grape Wine Res.*, **18**, 20-28.

Noda A., Kusunoki S., Yoshimura J., Yoshimura H., Oouchi K. and Mizuta R., 2008. Global warming projection by an atmospheric general circulation model with a 20-km grid. In : *High Resolution Numerical Modelling of the Atmosphere and Ocean. Global and Regional Climate Models*. Hamilton K. and Ohfuchi W. (eds.), Springer Verlag, Berlin, pp. 113-128.

Oliveira M., 1998. Calculation of budbreak and flowering base temperatures for *Vitis vinifera* cv. Touriga Francesa in the Douro region of Portugal. *Am. J. Enol. Vitic.*, **49**, 74-78.

Parker A.K., De Cortazar-Atauri I.G., Van Leeuwen C. and Chuine I., 2011. General phenological model to characterise the timing of flowering and veraison of *Vitis vinifera* L. *Aust. J. Grape Wine Res.*, **17**, 206-216.

Ruml M., Vukovic A., Vujadinovic M., Djurdjevic V., Rankovic-Vasic Z., Atanackovic Z., Sivcev B., Markovic N., Matijasevic S. and Petrovic N., 2012. On the use of regional climate models : implications of climate change for viticulture in Serbia. *Agric. Forest Meteorol.*, **158-159**, 53-62.

Tomasi D., Jones G.V., Giust M., Lovat L. and Gaiotti F., 2011. Grapevine phenology and climate change : relationships and trends in the Veneto Region of Italy for 1964–2009. *Am. J. Enol. Vitic.*, **62**, 329-339.

Tonietto J. and Carbonneau A., 2004. A multicriteria climatic classification system for grape-growing regions worldwide. *Agric. Forest Meteorol.*, **124**, 81-97.

Vera C. and Silvestri G., 2009. Precipitation interannual variability in South America from the WCRP-CMIP3 multi-model dataset. *Clim. Dyn.*, **32**, 1003-1014.

Webb L.B., Whetton P.H. and Barlow E.W.R., 2007. Modelled impact of future climate change on the phenology of winegrapes in Australia. *Aust. J. Grape Wine Res.*, **13**, 165-175.

Webb L.B., Whetton P.H., Bhend J., Darbyshire R., Briggs P.R. and Barlow E.W.R., 2012. Earlier wine-grape ripening driven by climatic warming and drying and management practices. *Nat. Clim. Change*, **2**, 259-264.

Wilby R.L., Troni J., Biot Y., Tedd L., Hewitson B.C., Smith D.M. and Sutton R.T., 2009. A review of climate risk information for adaptation and development planning. *Int. J. Climatol.*, **29**, 1193-1215.

Winkler A.J., Cook J.A., Kliewer W.M. and Lider L.A., 1974. *General Viticulture (4th Ed.)*. University of California Press, Berkley.