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Beniston, Martin

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Sustainability of the landscape of a UNESCO World Heritage Site in the Lake Geneva region (Switzerland) in a greenhouse climate

Martin Beniston*
Chair for Climate Research, University of Geneva, Switzerland

ABSTRACT: This paper poses the question as to whether the vineyards of the Lavaux region in the eastern part of Lake Geneva, Switzerland, will be able to maintain in a future greenhouse climate the same 'cultural landscape' as presently. It is indeed this landscape which has recently been placed on the list of UNESCO World Heritage sites, but whether it will remain as it has since the 13th century is an open question. The projected shifts in temperature and moisture patterns from current to future climate suggest that the grape varieties cultivated in the Lavaux region are likely to be subject to increasing heat and drought stress. As a result, the grape varieties that are currently cultivated in the region may no longer be sustainable; however, the visual aspect of the vineyards could be maintained if other grape varieties were to be planted, for example those that are endemic to warmer and drier Mediterranean-type climates. The scenery of the region would thus remain close to what it is today, even though the wine produced from other types of grape would certainly be different from those for which the Lavaux has become famous over the centuries. Copyright © 2007 Royal Meteorological Society

KEY WORDS climatic change; climate-landscape interactions; sustainability; vineyards; grape varieties

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1. Introduction

The Lavaux vineyards on the south-facing slopes of Lake Geneva, between Lausanne and Montreux in western Switzerland (see map in Figure 1) have been cultivated since the 13th century and have recently been included (June, 2007), in the register of the UNESCO World Heritage sites. However, many natural or semi-natural landscapes that are in the UNESCO's inventory are not immune to change, and particularly, those elements of landscape that are sensitive to climate variability and long-term warming may in time no longer resemble the original landscape that motivated its protection by UNESCO. The Swiss Jungfrau-Aletsch Glacier region that encompasses the European Alps' largest glacier and the surrounding mountains is one example of a UNESCO heritage landscape that is already subject to rapid rates of change, and will increasingly be under pressure as climate warms in the course of the 21st century.

In the case of the Lavaux vineyards, a warmer climate with significant shifts in seasonal precipitation (e.g. Beniston, 2006; Beniston *et al.*, 2007) is likely to increase the vulnerability of the grape vines and the natural or semi-natural vegetation that is contained within the geographical boundaries of the heritage site. Indeed, the rate of climatic change already observed over the past decades in this part of the Alps (e.g. Beniston, 2004a) suggests that it is one of the regions of Europe where, if current trends continue, future warming may be particularly strong and the impacts on water and biodiversity may be significant.

This paper will show that despite the projections of climatic change for the region over the next decades, it may be possible to sustain the esthetic features of the Lake Geneva vineyards. This will certainly require some form of adaptation that may involve changing the grape varieties, so that visually, the salient features of the landscape remain essentially unchanged from the point of view of a lay person, even though the types of wine that would be ultimately produced may no longer be those that the local communities have been producing for quite a few centuries.

2. Observational and simulated data

There is a reasonable degree of confidence in the quality of climatological data for a number of Swiss locations managed by MeteoSwiss, the Swiss weather service, as has been shown in previous publications (e.g. Beniston, 2004b, 2005, 2006), particularly because the daily data has been homogenized for many of the sites (Begert *et al.*, 2003). The data from the closest observational station to the Lavaux World Heritage Site, Montreux (location in Figure 1), spanning a 75-year period from 1931 has been used for this study to highlight current trends and how these may compare to those in a 'greenhouse

* Correspondence to: Martin Beniston, Chair for Climate Research, University of Geneva, Switzerland. E-mail: Martin.Beniston@unige.ch

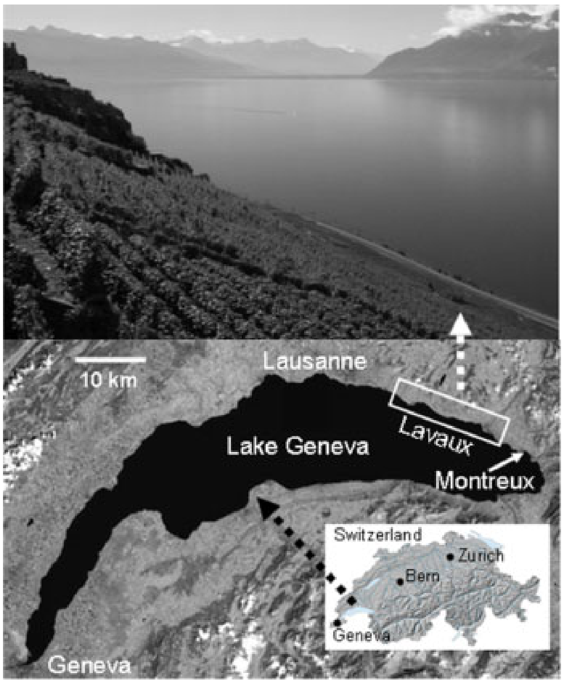

Figure 1. Photo of the Lavaux region (taken by the author on 7 July 2007), and map showing the location of the Lavaux (satellite photo of the Lake Geneva region courtesy of NASA WindWorld). This figure is available in colour online at www.interscience.wiley.com/ijoc

climate'. A suite of regional climate models (RCMs) has been applied to the investigation of climatic change over Europe for both the reference period 1961–1990 and for the last 30 years of the 21st century (2071–2100), in the context of a major European project entitled PRUDENCE (Christensen *et al.*, 2007).

The results of the PRUDENCE simulations has enabled quality testing of model results based on control simulations for the reference period (e.g. Déqué *et al.*, 2007), and subsequently to assess changes in a number of key climate variables. The scenario climate data used in the present paper are based on a composite of four RCM simulations, as applied in a recent paper by Beniston (2007), namely the Danish HIRHAM, the Swiss CHRM, the Italian ICTP and the Swedish RCAO models (see Beniston *et al.*, 2007 for further references).

The models operate at a 50-km resolution using the IPCC SRES A2 scenario (Nakicenovic *et al.*, 2000), that assumes a high level of emissions in the course of the 21st century, resulting from low priorities on greenhouse-gas abatement strategies and high population growth in the developing world. The A2 scenario implies a rise of atmospheric CO_2 levels to about 800 ppmv by 2100 (i.e. three times their pre-industrial values) and provides an estimate of the upper bound of climate futures discussed by the IPCC (2007). The fully coupled ocean-atmosphere general circulation model (GCM) of the UK Hadley Centre, HADCM3 (Johns *et al.*, 2003) has been used to drive the higher-resolution atmospheric HadAM3H model (Pope *et al.*, 2000), that in turn provides the initial and boundary conditions for the RCMs used in the PRUDENCE project.

3. Observed and projected climatic change in the Lavaux region

The climate of the Lavaux region is milder than its immediate surroundings because of its south-facing slopes and the modulating effects of Lake Geneva. While technically not Mediterranean climate, this part of the lake exhibits characteristics that are closer to Mediterranean-type regimes than the mountain and continental climates that prevail just a few kilometers away.

Wintertime minimum temperatures, computed on the basis of December, January and February means, are those that exhibit the strongest warming, as shown in the upper left-hand segment of Figure 2 for the period 1931–2005. The grey shading corresponds to the 95% quantile range for the reference time frame (i.e. spanning the 2.5% to the 97.5% quantile). Any part of the curve outside the shaded zone can be considered to depart significantly, in statistical terms, from the normal range of variability. In the past 75 years, winter minima have risen from about $-0.5\,^{\circ}$C in the 1930s to $+1.8\,^{\circ}$C in the 1990s, i.e. an increase of more than $2\,^{\circ}$C that is substantially more than the global-average warming of about $0.7\,^{\circ}$C in the same period (e.g. IPCC, 2007). The rise in observed wintertime minima are certainly not only the consequence of the enhanced greenhouse effect in the recent part of the record but are also related to decadal-scale forcing factors such as the North Atlantic Oscillation (NAO) that has been shown by Hurrell (1995) and others to strongly modulate climate on both sides of the Atlantic. Since the middle of the 1980s, minimum winter temperatures have never been below freezing while this was almost systematically the case prior to the 1970s.

The maximum summer temperatures (averaged for June, July and August) shown in the lower left-hand segment of Figure 2 do not mimic the minimum winter temperature trends, but nevertheless, have risen by about $1.3\,^{\circ}$C since the coldest part of the record in the 1960s. One of the reasons for this differential behaviour in trends is that the 1940s experienced very warm summers centred on the warmest year (1947), which is not so conspicuous in the wintertime record. Indeed, even though the warmest day on record in Montreux was during the 2003 heat wave (August 11), the summer average of 2003 was slightly lower than the 1947 record (unlike many other sites in Switzerland where, overall, the summer of 2003 was indeed the record breaker). Despite the fact that there has been a rise in average summer temperatures since the early 1990s, there is, for the moment, no evidence of a clustering of hot summers as was the case in the 1940s and early 1950s.

Using RCM results for the high-emissions A2 scenario (Nakicenovic *et al.*, 2000), the changes in the 30-year winter average minimum and the summer average maximum temperatures between the reference 1961–1990 and the target 2071–2100 periods are shown in the upper and lower right-hand segments of Figure 2, respectively. Average 30-year temperatures rise by close to $3\,^{\circ}$C in winter and by over $6\,^{\circ}$C in summer. The stronger summertime warming can be largely attributed to reduced

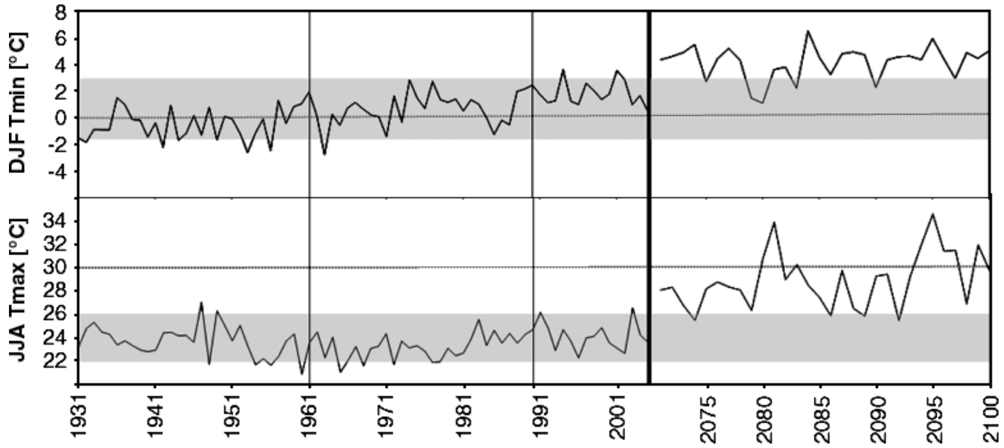

Figure 2. Winter minimum (upper) and summer maximum (lower) temperatures observed in the Lavaux region from 1931 to 2005 (left-hand segments) and simulated for the IPCC SRES A2 scenario from 2071 to 2100. Grey shading represents the 95% interval of climate variability for the 1961–1990 reference period, highlighted in these graphs by the vertical lines that delimit the 30-year baseline.

cloudiness in summer and greater soil-moisture deficits than under current climates because of the reductions in precipitation in all seasons other than winter, as discussed below. During the 2003 heat wave, the positive feedbacks from dry soils were seen to be a major driving factor of enhanced low-level atmospheric warming, as reported *inter alia* by Seneviratne *et al*. (2006). The inter-annual variability is seen in both figures to be greater than under current climate, and in almost all years the minimum and maximum temperatures are significantly different from the 95% range of variability of the reference climate.

Precipitation in the baseline climate is on average close to 1000 mm/year, but increased by about 10% following the 1976 summer drought with an average of over 1100 mm/year from the end of the 1970s to the mid-1990s, as seen in Figure 3. In the last decade, annual precipitation has dropped to below its long-term average value. Variability of precipitation, both in intra-annual (not shown here) and inter-annual terms is high, ranging from less than 650 mm in 1962, 2003 and 1976 (the three driest years of the record) to over 1300 mm in 1995, 2001 and 1977 (the three wettest years). While this represents a ratio between lowest and precipitation levels that is over a factor of 2, there is no obvious clustering of either very dry or very wet years that could result in compounded impacts on vegetation or water availability in the region. On the whole, precipitation is fairly evenly distributed throughout the year, the driest season being winter and the wettest being the summer, which is the season during which convective precipitation is most common and thus cumulative rainfall is at a maximum. Seasonal trends from 1931–2005 exhibit increases in precipitation totals in all seasons except for summer.

In the climate scenario, precipitation regimes are seen in Figure 4 to exhibit significant seasonal shifts, as was shown by Christensen and Christensen (2003) for much of Europe and Beniston (2006) for the Swiss Alps. Wintertime precipitation may increase by 30% in the Lavaux region and decrease in the other seasons with the greatest reduction in summer (−22%). The annual precipitation totals of 950 mm remain, however, close to those of the reference climate, but because vegetation is governed more by water availability at critical times of the growing period than by mean annual rainfall (e.g. water availability at the time of maturation of the grapes; see for example Zufferey and Murisier, 2004), changes in seasonal precipitation will be more of a determining factor on growth than the relative stability of annual precipitation.

The climatic conditions during the 20th century have rarely been extreme to the extent that they have resulted in significant damage to plants and vegetation in the Lavaux region; the biggest threat to the vines has not come from the range of precipitation or temperatures summarized here, but from short-lived intense convection and hailstorms. The phenology of the grapes can change from one year to another according to general weather characteristics, and quality of wines also varies between warm, dry years and cool, moist years. But apart from the damaging hail, the Lavaux vineyards have never experienced significant shortfalls in harvest, showing that the vegetation is in reasonable balance with the range of climate variability that exists in the region.

According to the RCMs, the number of very cold days (threshold of −10 °C) may diminish from 15 days per decade in the reference climate to 3 days per decade in the scenario climate. The number of spring frost days that can be damaging in the early flowering phases of the plants, drops from more than four events per year to less than one per year. The summer heat of future decades will be a major and quasi-systematic stress factor for vegetation, compared to the baseline climate.

Table I shows the number of days that exceed the 25, 30, 35 and 40 °C thresholds for both 1961–1990 and 2071–2100; the heat wave statistics of the summer of 2003 have been added for comparison purposes. It is seen that although the 2003 event was severe, it remains less so than the heat wave summers of the future, where 2003-type events may well occur at least once every alternate summer (e.g. Schär *et al*., 2004).

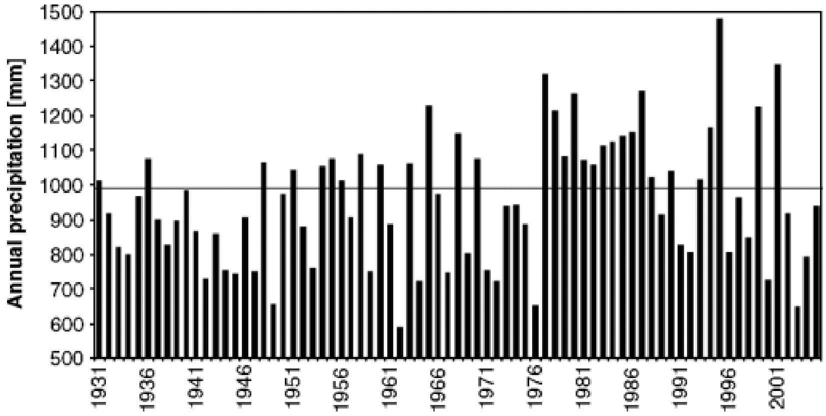

Figure 3. Annual precipitation totals observed in the Lavaux region from 1931–1990. The horizontal dashed line at 995 mm indicates the 1961–1990 average.

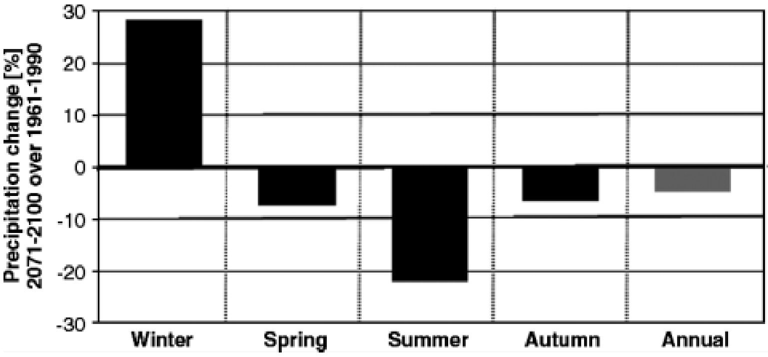

Figure 4. Seasonal changes in precipitation according to model simulations for the A2 scenario.

Table I. Changes between temperature threshold exceedances (number of days per year) in the Lavaux region for the reference and the scenario climate. The 2003 heat wave statistics are included for comparison purposes.

	>25 °C	>30 °C	>35 °C	>40 °C
1961–1990	28	4	0.15	0
2071–2100	92	41	11	2
2003	78	34	4	0

Both extremes of precipitation tend to increase in the scenario climate in the Lavaux region; the number of dry days increases by 10–20% according to the RCM chosen, while all models used for this study agree on a doubling of precipitation events beyond the 100 mm/day threshold, from three events per decade to about six per decade. The major problem for the Lavaux vineyards is related to hailstorms, which the RCMs are incapable of reproducing; it can only be surmised that if the number of days with very heavy rainfall increases, then so does the number of days with damaging hail.

4. Potential impacts for the vineyards and vegetation of the Lavaux region

In general, grape cultivation takes place in climates whose mean annual temperature lies between 10 and 20 °C (e.g. Tonietto and Carbonneau, 2004) according to the grape variety. It is true to say that over the past couple of decades, the quality of many wines has improved in many wine regions, in part due to new wine maturation techniques, but also due to an increase in average temperature in most regions where vines are cultivated. In the Lavaux heritage site, the mean annual temperature of the baseline 1961–1990 period is close to 11 °C in the lower part of the vineyards, and about 9 °C in the upper parts. According to RCM projections through to the end of the 21st century, mean temperatures will rise by 4–6 °C on an annual-average basis, implying that even in a future climate, the vineyards will remain within the commonly accepted range for vine cultivation. The question that remains open, however, is to assess whether the dominant grape species in the Lavaux (*Chasselas*) would be able to withstand the water and heat stress that are likely to be common in the next decades. Seeing the exceptional quality of the 2003 harvest and the resulting wines for that year, one would be tempted to conclude that a warmer climate with hot, dry summers, may be good news for the region. It is more likely, however, that if 2003-type summers were to occur every other year rather than very occasionally, the cumulative impacts of drought and heat may impose severe constraints on the physiology of the plants.

One limiting factor in the future will certainly be soil-moisture availability; with sufficient water in the soils,

Table II. Climate statistics related to the vegetation period, for the baseline climate 1961–1990 and the scenario climate 2071–2100. The average 30-year beginning and end of the season beyond the given threshold are shown, as well as the degree-days beyond the selected threshold. Statistics for the 2003 heat wave are also provided for comparison.

	5 °C threshold				10 °C threshold			
	Start	End	Duration	DD >5 °C	Start	End	Duration	DD >10 °C
1961–1990	11 Mar	20 Oct	255 days	3,462	18 Apr	19 Sep	185 days	2,948
2071–2100	5 Jan	21 Dec	351 days	4,959	8 Apr	3 Nov	210 days	3,939
2003	26 Feb	6 Dec	284 days	4,140	14 Apr	20 Sep	190 days	3,471

plants are capable of weathering an extended period of drought and heat. However, because drought tendency is projected to begin in the late winter and early spring in the scenario climate, soil moisture will probably decline to below critical levels, particularly if there is a succession of dry years during which precipitation may no longer be sufficient to recharge ground water. Moderate water stress for grapes begins when the stem water potential is below the 20% threshold (Dry and Loveys, 1999; Naor, 1998; Chone *et al*., 2001), and severe stress occurs when this potential is less than 8%. During the 2003 heat wave, moderate water stress was recorded for 60 days and severe stress for 1–2 days. In the scenario climate, these figures will rise on average to over 100 days for moderate stress and 60–70 days for extreme stress. Under conditions of water stress, plants are capable of developing survival strategies that allow them to survive adverse climatic conditions. The closure of the stomata at the surface of the leaves reduces evapotranspiration, and a CO_2-enriched atmosphere increases the efficiency of plants' resistance to drought (e.g. Turner, 1979; Körner and Larcher, 1988). However, a repetition of water stress conditions year after year would take a heavy toll on the survival of the current grape variety, as the survival strategies may be effective for isolated and relatively short extreme events but probably not for recurrent extremes.

In addition to the important constraints that drought and excessive heat impose on vines, subtle changes may occur in the phenology cycles of the plants. Plant phenology relates climatic parameters to stages of the physiological development of plant species, such as the period of flowering or senescence of a particular species. Phenology can thus provide an indicator as to long-term changes in climate if, for example, blooms occur earlier in the year compared to a given baseline. One commonly used indicator for plants is the number of degree-days (DD), a term that represents the aggregate of temperatures above a particular threshold level, and can be roughly equated with the energy available for plant growth. In a changing climate, DD will change considerably, and will result in earlier flowering and an earlier harvest, which in turn is likely to result in different quantities of sugar in the grapes and thus on the quality of the wines that will be produced. Taking two threshold levels for counting DD, Table II shows the large changes that will occur in the length of the vegetation period; the energy-equivalence of changes in DD increases by 45% beyond the 5 °C threshold, and 35% beyond the 10 °C threshold, which is substantially more than what was recorded during the 2003 event, also shown in this table for comparison purposes.

5. Conclusions

Because of the strong shifts in climate that climate model simulations project by 2100 in the regions that encompass the vineyards of the Lavaux World Heritage Site, it is expected that the productivity of the vines and their vulnerability to heat and drought stresses will change to a large degree. While the detrimental effects of damaging frosts in the spring will be considerably reduced, the vines may suffer physiological damage in the warmer months of the year, prior to the time of grape harvesting. The long experience of the wine growers in the region, based on heat waves and prolonged drought in past decades and centuries may not be sufficient to address the issues of a climate that will exhibit a much higher frequency of heat and drought events in the future. This is because an isolated drought or heat wave can probably be weathered by the plants, whereas when the extremes recur regularly, the response of vegetation and the conditions for its survival (e.g. soil moisture) will be different.

However, the Lavaux will not become a barren zone, because direct human intervention can help maintain the landscape as it has been since the first vineyards were planted in the 13th century. Irrigation techniques can allow the vines to flourish if the heat stress is not too great; and new grape varieties that are adapted to drier and warmer conditions, as in the case of Mediterranean varieties that are commonly found in Italy, Greece, Spain (*Merlot, Shiraz*) could be planted. This would certainly pose challenges to the wine growers to commercialize wines that have never been cultivated in the Lavaux region, but would at least guarantee that the landscape of vineyards rising uphill from Lake Geneva, that the UNESCO World Heritage Site aims to protect, would be as visually pleasing as it has been for centuries.

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