queretin-3-glucuronide occurs mainly during flowering, while after veraison quercetin-3-glucoside and quercetin-3-rhamnoside are accumulated.

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ECA&D: A high-resolution dataset for monitoring climate change and effects on viticulture in Europe

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ABSTRACT
Climate change will lead to persistent changes in temperature and precipitation patterns which will affect the characteristics of wine produced in each region. The European Climate Assessment and Dataset (ECA&D) is a web-based database and tool to monitor climate variability and trends over Europe. This tool is used in this study to analyse the viticulture-specific Huglin Index and averaged temperature over the growing season.
The study quantifies the timing and the extent of the expansion of the regions in Europe
where two selected grapes can be used for viticulture. For the two grape varieties analysed, the expansion is northward and eastward and areas in southern Europe are indicated where climate is becoming too hot to produce high-quality wines.

Keywords: Europe, climate change, Huglin Index, growing season averaged temperature.

1 INTRODUCTION

Temperatures in Europe are rising faster than the global average [1]. With the warming of Europe, hot summers have occurred in the recent past which were unprecedented in the instrumental record, like the 2003 summer [2], surpassed in extremity by the recent 2010 summer [3].
The increase in frequency of extremely hot summers will affect viticulture and the general trend towards warmer conditions in Europe will impact on the extent of the area where vine cultivation is possible. Climate of new areas, which used to be not, or only marginally, suited to produce high-quality wines, now become warm enough to compete with the traditional wine-producing areas [4]. Moreover, the areas which have been associated with a particular grape variety for centuries may face the situation of adverse climatic conditions for this particular grape.
There are numerous efforts to capture the suitability of a region and its climate in terms of relatively simple climatic indices claiming to reliably describe the potential of grapes to grow and ripen [5], while others identify more complex processes, like vine water stress, which relate climate and soil to the quality of grapes [6]. In this study we confine ourselves to the popular, temperature-based Huglin index [7] (HI) and growing season averaged temperature [5, 8] (Tavg).
Jones et al. [5] remark that future climates may bring 'potential geographical shifts and/or expansion of viticulture regions with parts of southern Europe becoming too hot to produce high-quality wines and northern regions becoming viable'. Here we test if a change in viticulture regions can already be observed from the ECA&D station data focussing on two selected grape varieties.

2 MATERIALS AND METHODS

2.1 Description of the dataset

The data used in this study are from the European Climate Assessment & Dataset (ECA&D, http://www.ecad.eu [9]). ECA&D is a collection of daily station observations of currently 12 elements and contains data from nearly 6600 European stations and is gradually expanding. Data from the station network

at ECA&D is updated on a monthly basis using data kindly provided by mainly the National Meteorological and Hydrological Services. On the basis of the daily data, a set of 70 climate indices are calculated. Each index describes a particular characteristic of climate change (both changes in the mean and the extremes).
The spatial extent of ECA&D covers the whole of Europe including Turkey, Northern Africa and the Middle East. However, the station data availability at the southern and eastern edges of the domain is poor.

2.2 Huglin and average temperature over the growing season

The two temperature-based indices or measures used in this analysis describe wine-region climate characteristics and cultivar suitability. The Huglin index (HI) is a heat summation index taking daily average temperature and daily maximum temperature into account as well as an adjustment for day length. Jones [5, 8] has established grapevine climate-maturity groupings based on the growing season averaged temperature (April 1 – Oct. 31). Grape varieties are classified within these climate/maturity groupings with a minimum and maximum value. Table 1 shows two popular and illustrative grape varieties with the minimum HI values and the range in average growing season temperatures according to Jones.

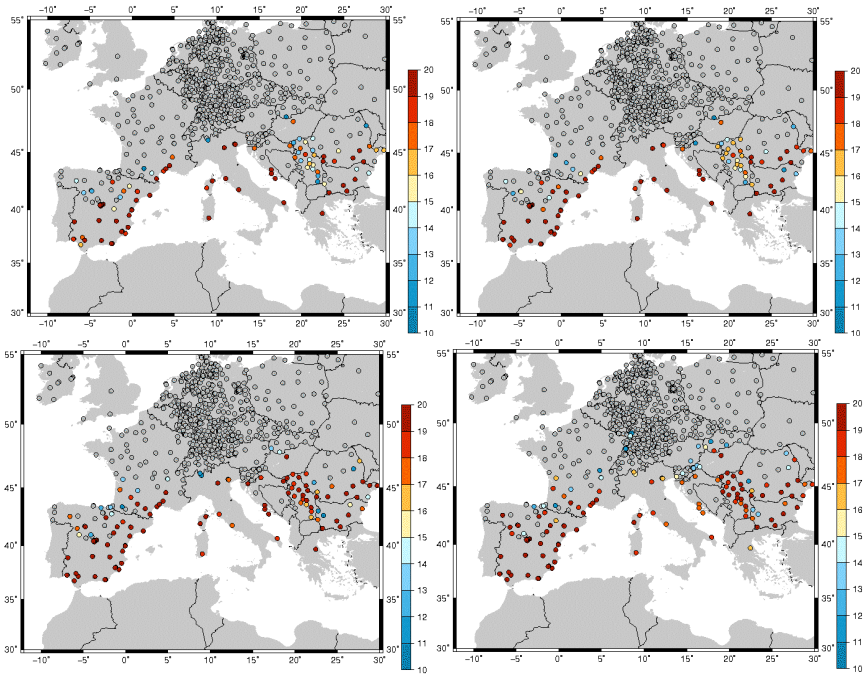

Figure 1. Shown are the number of years, in a 20 year time span, in which the Huglin index exceeds the 1900 threshold (associated with Merlot noir). The time spans used are 1961-1980 (upper left), 1971-1990 (upper right), 1981-2000 (lower left) and 1991-2010 (lower right). Grey circles show stations that fail to exceed the threshold ten times or more.

Table 1. Two grape varieties with the minimum Huglin [7] values ($^{\circ}C$) and the range in average growing season temperatures ($^{\circ}C$) according to Jones [5, 8].

Grape	Jones' min.	Jones' max.	Huglin
Sauvignon blanc	14.64	17.76	1700
Merlot noir	16.04	18.84	1900

3 RESULTS AND DISCUSSION

3.1 Huglin index

Figure 1 uses a simple diagnostic to demonstrate the northward expansion of areas where grape varieties with a minimum Huglin index of 1900, like Merlot noir, can be cultivated. The number of years in a 20-year interval which exceeds the minimum Huglin threshold values for Merlot noir is calculated for four overlapping intervals: 1961-1980, 1971-1990, 1981-2000 and 1991-2010. This figure shows that stations which were marginally suited to grow Merlot noir have become more suitable and that stations further north have changed from unsuitable to marginally suited. This is particularly evident in the Balkan Peninsula and stations in the south western part of France.

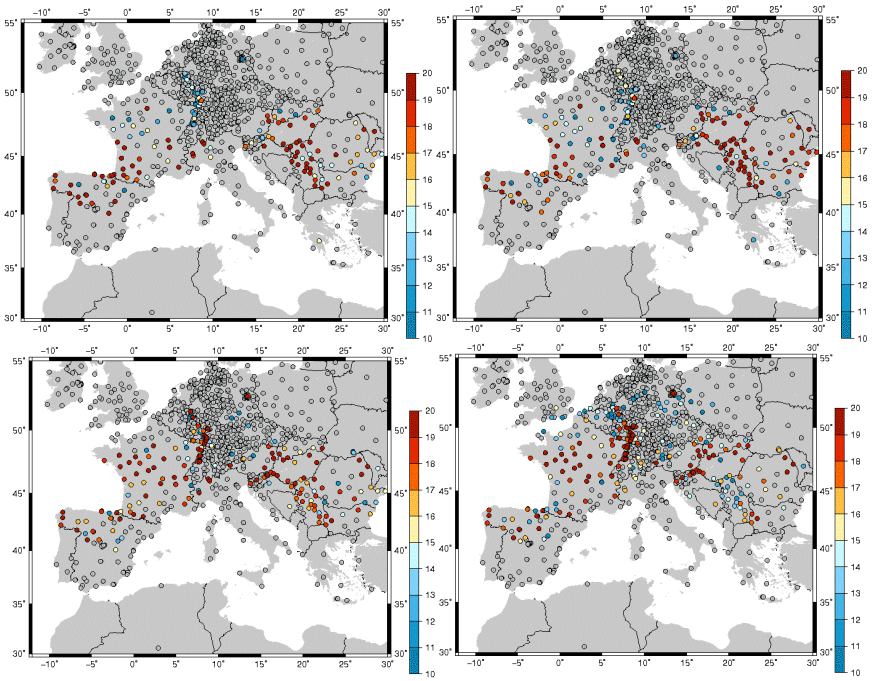

Figure 2. Shown are the number of years, in a 20 year time span, in which the average growing season temperature is within the bounds specified in Table 1 for Sauvignon blanc. Grey circles show stations outside these bounds. The time spans used are 1961-1980 (upper left), 1971-1990 (upper right), 1981-2000 (lower left) and 1991-2010 (lower right).

3.2 Growing season averaged temperature

Figs. 2 and 3 show the number of years in overlapping 20-year time intervals which have average growing season temperatures between the lower and upper thresholds. These figures show that stations which were marginally suited to grow the particular grape variety have become more suitable and that stations further north have changed from unsuitable to marginally suited.

Sauvignon blanc is grown in the Bordeaux region as well as in the Loire Valley in France. Fig. 2 indicates optimal conditions in the 1961-1980 period in Bordeaux with somewhat less optimal conditions in the Loire Valley. In the most recent interval, 1991-2010, this situation seems to have been reversed with optimal conditions in the Loire Valley and deteriorating conditions in the Bordeaux region.

The area in Italy where Merlot noir is popular, the wine region Friuli in the northeast, the conditions to this grape are becoming less optimal (fig. 3), while in Hungary and Burgenland (eastern Austria) the conditions are improving, explaining the increase in plantings of Merlot noir in that area in recent years [10]. Conditions in the Balkan Peninsula have improved as well with the exception of the station in Greece. Merlot noir is most prominent in southwest France in regions like Bordeaux, Bergerac and Cahors where the number of years in the twenty-year intervals with average growing season temperatures between the Jones' thresholds has initially increased to nearly twenty for many stations in the 1981-2000 period. However, the figure shows that the number of years in the most recent period 1991-2010 has decreased again indicating that too hot conditions have become more common.

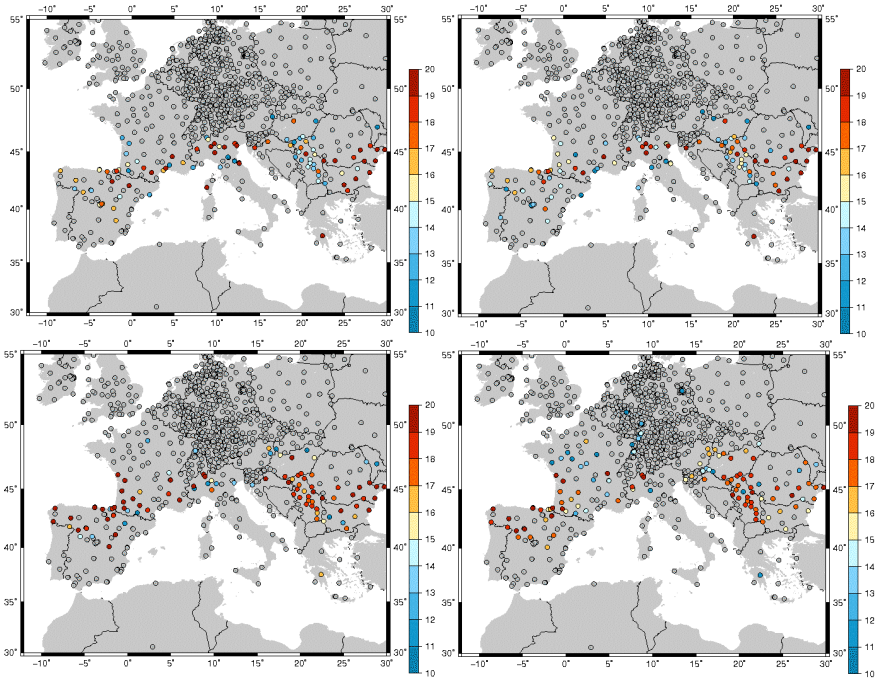

Figure 3. Shown are the number of years, in a 20 year time span, in which the average growing season temperature is within the bounds specified in Table 1 for Merlot noir. Grey circles show stations outside these bounds. The time spans used are 1961-1980 (upper left), 1971-1990 (upper right), 1981-2000 (lower left) and 1991-2010 (lower right).

4 CONCLUSIONS

Using temperature data from a dense network of meteorological stations in Europe the Huglin Index (HI) and simple averaged temperature over the growing season (Tavg) are calculated.

Common to the indices is that they indicate a northward and eastward spread of the area where viticulture for the selected grapes is possible. It is also shown that some areas are already too hot to produce high-quality wines. This observation is under the reservation that the use of hard-limit thresholds as done in this study, will insufficiently reflect the ability of the grapes to grow under stressed conditions.

In closing it must be readily admitted that many aspects of the process of growth and ripening of the grapes in response to climatic variations are not captured with the simple temperature-based indices used here. A more comprehensive study, using more realistic indices should give a more precise view of the effects of climate change on viticulture.

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