# Grapevine bioclimatic indices in relation to climate change: a case study in the Portuguese Douro Demarcated Region.

Daniel Blanco-Ward, Alexandra Monteiro, Myriam Lopes, Carlos Borrego, Carlos Silveira, Ana Miranda
Department of Environment and Planning (DAO) & CESAM, Aveiro University
3810-193 Aveiro, Portugal
dblancoward@ua.pt

António Ribeiro, João Andrade, Manuel Feliciano, João Castro, David Barreales
Mountain Research Centre (CIMO), School of Agriculture, Polytechnic Institute of Bragança, Campus de Santa Apolónia,
5300-253 Bragança, Portugal

Carolina Viceto, Alfredo Rocha
Physics Department & CESAM, Aveiro University
3810-193 Aveiro, Portugal

Cristina Carlos
Association for the Development of Viticulture in the Douro Region (ADVID),
5050-106 Peso da Régua, Portugal

Carlos Peixoto
Casa Ramos Pinto
5150-338 Vila Nova de Foz Côa, Portugal

***Abstract*— Climate change is of major relevance to wine production as most of the wine-growing regions of the world, in particular the Douro region, are located within relatively narrow latitudinal bands with average growing season temperatures limited to 13-21ºC. This study focuses on the temporal variability of three grapevine bioclimatic indices, which are commonly used as part of the Geoviticulture Multicriteria Climatic Classification System (MCC) to classify the climate of wine producing regions worldwide. Dynamical downscaling of MPI-ESM-LR global data forced with RCP8.5 climatic scenario is performed with the Weather Research and Forecast (WRF) model to a regional scale including the Douro valley of Portugal for recent-past (1986-2005) and future periods (2046-2065; 2081-2100). Results indicate significant shifts towards warmer and dryer conditions during the growing season and higher night temperatures during the grape ripening period. An assessment on the statistical significance of the differences between the recent-past and the future scenarios and the potential impact on wine production in the study area is performed. These results will provide evidence for future strategies aimed to preserve the high-quality wines in the region and their typicality in a sustainable way.**

***Keywords*— climate change, grapevine bioclimatic indices, wine production, Douro valley**

## I. INTRODUCTION

There is a general acceptance by the scientific community of the reality of climate change in relation to human activities, especially concerning greenhouse gases (GHGs) emissions. Depending on the GHGs emissions scenario, it is expected an increase in global mean surface temperature from 1ºC to 3.7°C by the end of the century when compared to the reference period 1986-2005 [1]. The influence of climate is critical in viticulture and wine production with climate having a greater impact on yield and quality than other environmental factors such as soil type or grapevine variety. Year-to-year meteorological variations affect the yield and the optimal environmental conditions for the grape to ripe and, therefore, whether wine typicity for a given 'terroir' or grapevine growing region will be correctly expressed to achieve its full potential [2].

Most of the wine-growing regions of the world, in particular the Douro region, are located within relatively narrow latitudinal bands with average growing season temperatures limited to 13-21ºC. Therefore, small changes in temperature could end affecting the typicity and styles of the wine produced in them, and even produce shifts in their potential for viticulture, making it too warm or better suited to produce quality wines than before [3].

The Multicriteria Climatic Classification System (MCC System) for grape growing regions worldwide [4] has been already used to assess the impact of climate change on the suitability for wine production across Europe. The indices were calculated from climate variables obtained from simulations with a grid size of about 25 km performed with the regional climate model COSMO-CLM for the recent-past climate (1960-2000) and for the 21st century (2011-2040, 2041-2070 and 2071-2100) under the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios (IPCC-SRES) B1 and A1B. The A1B scenario corresponds to a balance across all energy sources, whereas in the B1 scenario the emphasis is on environmental sustainability. All simulations were forced by ECHAM5/MPI-OM1 boundary conditions. The results of this study indicated an increased soil water deficit and cumulative thermal effects during the growing season in southern Europe, which could imply negative effects for wine production for these areas unless suitable adaptation measurements (e.g. rootstock and variety selection, training system, irrigation) are taken. In contrast, western and central Europe could benefit with higher quality potential for the grape and even new potential areas for wine production [5].

In another study, the atmospheric variables taken from coupled global and regional climate models (GCM-RCMs) simulations in combination with the MCC system were also used to assess present and future scenarios for the Portuguese grapevine growing regions. For present scenarios (1950-2000), the WorldClim project 1 km high resolution dataset [6],

Fundação para a Ciência e a Tecnologia (FCT)

validated with E-OBS observational data [7] was used. To assess the impacts of climate change on future viticulture suitability in Portugal, the period 2014-2070 under the IPCC-SRES A1B was chosen. An ensemble of 13 RCM simulations driven by 3 different GCMs produced by the ENSEMBLES project [8] was selected. To pass from the coarse grid RCM resolution 0.22° x 0.22° (~25 km) to the 1 km grid size of the WorldClim baseline dataset, a bi-cubical interpolation (pattern downscaling or 'delta' method) was used. The final results illustrated significant changes in the current bioclimatic viticultural Portuguese zones as they depict a lower bioclimatic diversity and a more homogenous warm and dry climate for most Portuguese wine regions [9].

The present research makes use of an ensemble of Weather and Research Forecasting (WRF) model simulations driven by two forcings, namely the European Reanalysis (ERA) Interim and the Max Planck Institute Earth System - low resolution model (MPI-ESM-LR). The simulations were performed for 20-year periods as adopted by the IPCC 5th Assessment Report [10], namely 1986-2005 for the recent-past, 2046-2065 for the mid-future and 2081-2100 for the long-future climate using the Representative Concentration Pathway (RCP) 8.5 new emission scenario [11]. More details on the climatological modelling can be found in the Data and methods section.

The ultimate purpose of this study is to evaluate whether the ERA-interim driven WRF simulations for the recent-past time period (1986-2005) can be used successfully to reproduce the climate of the Portuguese Douro Demarcated Region (DDR) as described by the Geoviticulture MCC system. The GCM MPI-ESM-LR driven simulations are used to assess the possible impacts of the estimated climate changes under RCP8.5 for the study area. Compared with other work previously done in the area, this study makes use of high-resolution 9 x 9 km WRF simulations under the new RCP 8.5 scenario.

## II. The Study Area

The Portuguese Douro Demarcated Region (DDR) runs along both margins of the Douro River from its midcourse in the East up to the border with Spain in the West. The western most area of the region is located 70 km from the Atlantic Ocean. The Douro Valley extends along 90 km in the West-East direction and along 50 km in the North-South direction (Fig. 1). The landscape is characterized by mountainous terrain, rising above the Douro River and its tributaries, with moderate to steep slopes and varying exposures. The geology of the Douro Valley is dominated by schistose-layered rock, oriented nearly vertical, with some outcrops of granite. The average elevation over the entire region is 443 m, but ranges from a low near 40 m to a high of just over 1,400 m [12]. The Region covers approximately 250,000 hectares with vineyard area representing roughly 43,480 hectares, 17.4% of the total land area. The DDR is divided into three sub-regions: Baixo Corgo with the smaller area (45,000 ha), Cima Corgo with an intermediate extension (95,000 ha), and Douro Superior with the largest extension (110,000 ha). The vineyard figures for these sub-regions are 13,368 ha, 20,270 ha and 9,842 ha respectively [13].

The region is characterized topographically by sloping vineyards arranged in various terraced configurations. These terraces were created and perfected throughout the centuries enabling man to cultivate vines on the steepest slopes. After the phylloxera epidemic, the devastated small terraces were abandoned and new, wider and steeper terraces were built, with or without supporting walls and allowing for a greater planting density (approximately 6,000 vines per hectare). It was then, too, that vineyards were planted according to the natural slope of the land. The introduction of mechanization to the region at the end of the 60's and early 70's, led to the appearance of a new cultivation system composed by horizontal terraces with earth supporting walls, each bearing 1-2 rows of vines and with a low planting density of some 3,000 to 3,500 vines/ha. More recently, as an alternative to the wide terraces, vines are being planted in vertical rows rising up the steeper hillsides. With a planting density similar to that of traditional vineyards (about 4,500 to 5,000 plants per/ha), this system is better adapted to small plots of land with up to 40% slopes and can be worked by mechanical means [14].

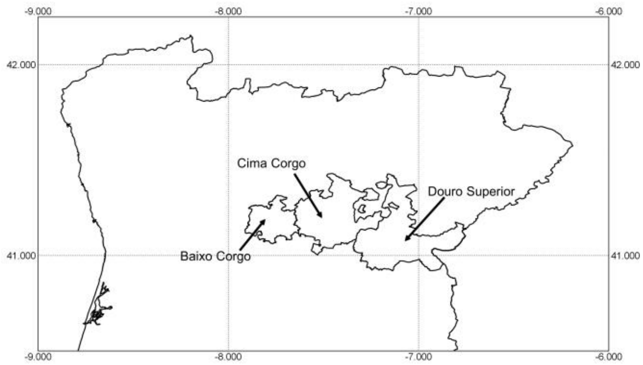


Fig 1. Douro Demarcated Region (Portugal).

The DDR has a Mediterranean climate, with highly variable rainfall events, concentrated in winter months, and hot summers. It is sheltered from Atlantic wet and cold winds by two mountain ranges, Marão and Montemuro, located at its western border. Temperature increases and precipitation decreases from West to East. The westernmost sub-region inside the Douro Valley (Baixo Corgo) is nearer to the Atlantic Ocean and therefore more affected by the moist maritime winds. The eastern most regions within the Douro Superior sub-area are more distant from the Atlantic Ocean therefore having a more continental climate influence. The region is classified as a warm temperate climate (Köppen Csb), with average annual temperatures during 1980–2009 of 15.4°C, average daily minima temperatures (T min) in the coldest month dropping to 2.7°C, and average daily maxima temperatures (T max) in the warmest month reaching 32.1°C [15]. Mean growing season temperature (GST) from April to September for the same climatological period is 20.6°C. Growing season precipitation (GSP) has a mean value of 193 mm, representing 30% of the annual total (624 mm). The average precipitation of the driest month (July) is just 11.2 mm. Low precipitation values along with high temperatures and high radiation exposure give rise to situations of intense summer plant-soil-water stress, particularly in the Cima Corgo and Douro Superior sub-regions [3].

Taking into account three meteorological stations representative of the three DDR sub-regions during 1980-2009, the Huglin Index (HI) in the area averaged 2,740 °C $d^{-1}$ whereas the dryness index (DI) had a mean value of -126 mm, and the cool night index (CI) one of 13.6 °C. In the Geoviticulture MCC System, the DDR climate is currently classified as HI+2/DI+2/CI+1 (Warm/Very dry/Cool nights) [4], [16]. Other renowned grape growing regions falling under this classification are the Napa Valley (US) and the Mildura wine distric (Australia) [4]. Although the Geoviculture MCC system is generally accepted as a useful tool to describe the climate of grape growing regions globally, it is advisable to keep in mind that there might also be considerable variations at the mesoscale due to different factors such as topography or distance to the sea [17]. In fact, values given for the Régua station within the Baixo corgo sub-region during 1951-80 were 2489 °C $day^{-1}$ for HI –close to the HI+1 2400 °C $day^{-1}$ limit of the temperate warm class-, -37 mm for DI –belonging to the DI+1 or moderately dry class-, and 12.8 °C for CI –falling inside to the same CI+1 category as the overall more recent classification- [18].

## III. DATA AND METHODS

### A. High resolution 9 x 9 km WRF climate simulations

Marta-Almeida et al. [19] performed an ensemble of WRF high-resolution climate simulations driven by two forcings, namely ERA-Interim reanalysis and the Max Planck Institute Earth System - low resolution model (MPI-ESM-LR). The reanalysis data were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) through the ERA-Interim project, with a horizontal resolution of approximately 79 km [20]. The MPI-ESM-LR is a global Earth System Model developed by the Max-Planck Institute, with a 1.9° horizontal resolution [21] which corresponds to about 160 km horizontal resolution. This model participated in the Coupled Model Intercomparison Project Phase 5 (CMIP5), which uses new emission scenarios, namely the RCPs.

Currently there is a new set of RCPs associated to future concentrations of GHGs in the atmosphere. In this study we used the RCP8.5, defined by a radiative forcing of 8.5 W $m^{-2}$ by 2100 and a continuous increase after this year [22]. The RCP 8.5 provides an updated and revised quantification of the original IPCC A2 SRES scenario [23].

The WRF high-resolution climate simulations were performed for 20-year periods as adopted by the IPCC 5th Assessment Report [24], namely 1986-2005 for the recent-past, 2046-2065 for the mid-future and 2081-2100 for the long-future climate. These simulations were implemented for three nested domains with increasing horizontal resolutions, namely 81, 27 and 9 km (Fig. 2). Validation of the WRF recent-past simulations driven by the two forcings with observational temperature and precipitation datasets for the Iberian Peninsula provided acceptable comparisons of the probability distributions of temperature and precipitation for both models, with WRF-ERA providing better results most of the times although there are occasions where WRF-MPI performed better [14].

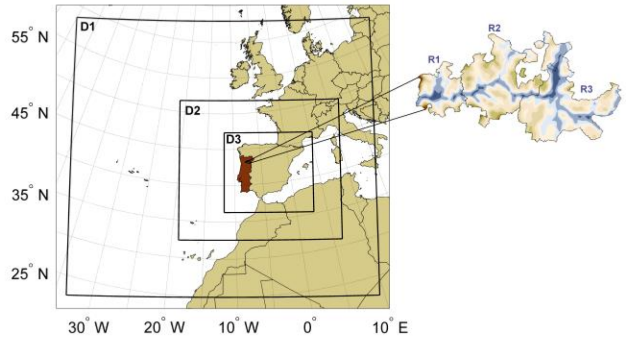


Fig 2. Nested model domains used in the regional WRF implementation with resolutions of 81 (D1), 27 (D2) and 9 (D3) km.

### B. Grapevine bioclimatic indices

Three specific grapevine bioclimatic indices were selected: the Heliothermal index of Huglin (HI), the cool night index (CI) and the dryness index (DI). These indices are commonly used to characterize grapevine growing areas worldwide in an standardized way [4].

The HI provides information regarding heliothermal and berry sugar potential:

$$HI = \sum_{April1st}^{September30th} \frac{(T\max - 10C^{\circ}) + (Tavg - 10C^{\circ})}{2} d$$
$$Tavg = \frac{T\max + T\min}{2} \quad (1)$$

Tavg is the mean air temperature (°C), Tmax is the maximum air temperature (°C), d is length of day coefficient ranging from 1.02 to 1.06 between 40° and 50° of latitude. A value of 1.02 was assumed for a latitude between 40°01’ and 42°00’. This index is usually calculated from monthly climatic means.

The purpose of CI is to improve the assessment on the grape qualitative potentials, notably in relation to secondary metabolites (polyphenols, aromas) in grape:

$$CI = \sum_{September1st}^{September30st} \frac{T\min}{30} \quad (2)$$

Finally, DI indicates the potential water availability in the soil, related to the level of dryness in a region. It is also related with the level of grape ripening and wine quality. It is computed as follows:

$$W = W_0 - P - T_v - E_s \quad (3)$$

Where W is the estimate of soil water reserve at the end of a given month, $W_0$ is the initial soil water reserve which can be accessed by the vine roots at that period of time, P total monthly precipitation, $T_v$ the potential transpiration of the vineyard and $E_s$ the direct evaporation from the soil. To compute $T_v$ and $E_s$ is also necessary to compute the monthly total potential evapotranspiration. This is usually done by the Penman-Monteith method but, as we only worked with temperature and precipitation records, it was approximated by the Hargreaves method, which produces comparable results in arid and semiarid environments and requires temperature data only [34]. For intercomparison reasons, W is also calculated sequentially on a monthly basis during the same period used for HI (from April 1st to September 30th), which is acceptable for most of grape growing regions in the northern hemisphere. The result is the DI and units are mm of water in the soil. The initial $W_0$ is usually taken as 200 mm.

### *C.* WRF cell selection and statistics

One 9 x 9 km cell representative for each of the three subdivisions (Baixo Corgo, Cima Corgo and Douro Superior) present in the DDR region was selected to compute the three bioclimatic indices for each year belonging to the simulated 1986-2005 recent-past period. This was done by taking into account the GST values for each WRF-ERA cell within the DDR limits at the same time they were overlain on mapped vineyard areas as provided by the CORINE 2009 dataset [25] in a Geographic Information System (GIS) set-up as illustrated in Fig 3 of the Results section. Tests for the significance of differences in means and variances of the statistical distributions of bioclimatic indices between the different 20-year periods (recent-past, mid-future, long-future) as modelled by the WRF-MPI-ESM-LR set-up were implemented in the data visualization and statistical programming software package R.

## IV. Results

### *A.* WRF-ERA data validation

The high-resolution WRF simulations forced by ERA-Interim reanalysis resulted in realistic patterns of surface atmospheric variables. Fig 3 shows the spatial pattern of the grapevine growing season average temperature (GST) over the Douro valley as modelled for the final nested highest resolution (9 x 9 km) domain. Within the DDR, the GST values portray an East-West trend resulting from the orientation of the main valley itself and the increasing distance from the sea.

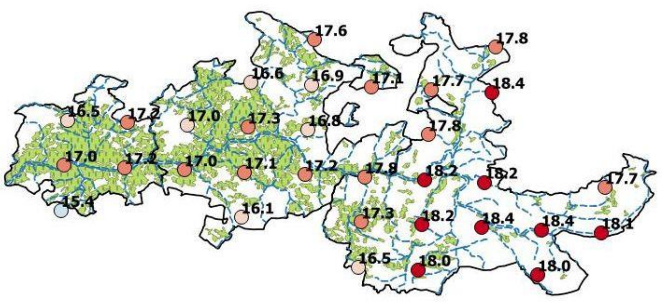

Fig 3. Growing Season Average Temperature (GST) as calculated by the 1986-2005 WRF-ERA simulation. The circles represent 9 x 9 km cell centres. Each WRF cell is associated with its GST value (°C). WRF cells with highest GST values are coloured with dark red tones whereas cooler areas are depicted with lighter red or even bluish tones. The DDR limits are represented with its main subdivisions (Baixo Corgo, Cima Corgo, and Douro Superior), main river courses and grapevine cultivated areas.

Table 1 portrays the WRF-ERA GST median statistics obtained for each one of the DDR sub-regions. The GST median values are close to those reported for the area by [3] based on the WorldClim 1 km x 1 km 1950-2000 database [6]. In fact, the average height of the selected WRF-ERA cells (416 m Baixo Corgo, 433 m Cima Corgo and 481 m Douro Superior) corresponds more to transitional sub-plateau locations than to sheltered valley areas where the Mediterranean climate characteristics are stronger.

TABLE I. GST STATISTICS FOR THE THREE DDR SUB-REGIONS.

| **1986-2005** | **GST medians** | |
|---|---|---|
| ***Region*** | ***Model*** | ***WorldClim*** |
| Baixo Corgo | 17.1 | 17.5 |
| Cima Corgo | 17.0 | 17.5 |
| D. Superior | 18.0 | 18.0 |

A closer inspection of the ombrothermic chart (Fig. 4) for the Douro superior WRF-ERA cell against climatological observations reported by an equivalent sub-plateau location in that sub-region, reveals a quite close match for precipitation (except for February and March). However, temperatures are significantly lower for all months (-1.8°C on average), which could be in part explained by the difficulty to reproduce the specific mesoclimates associated to the varied topography and shelter effects present in the area. WorldClim figures for annual precipitation in the Douro Superior sub-region are significantly higher (median 832 mm) than those reported by the literature for a sub-plateau location (in the order of 500 mm) [3], [26].

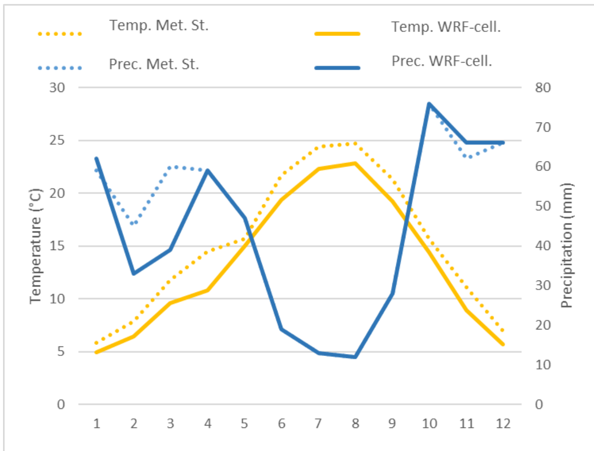


Fig 4. Ombrothermic chart comparing monthly average temperatures and total precipitations from the WRF-ERA cell selected within the Douro Superior region compared with literature sources [38]. Solid lines are for WRF-ERA cell data and dashed lines are for meteorological observations from the literature.

Results for the MCC bioclimatic indices under the ERA-Interim forcing for the Douro Superior cell are as following: 2177 °C day$^{-1}$ (HI), -22 mm (DI) and 12.5 °C (CI). These values correspond to a HI+1, DI+1, CI+1 (temperate warm, moderately dry, cool nights) global geoviticulture climate classification. Once again, these results are closer to what would be expected from a location exposed to a sub-Atlantic influence, such as a sub-plateau or a location less distant to the sea, rather than a sheltered bottom-valley location under stronger Mediterranean conditions.

### *B.* Grapevine bioclimatic indices and phenology fluctuations

Table 2 illustrates the differences found between the mean and the variance of the 20-year distributions of HI, DI, CI as obtained for the recent-past (1986-2005), mid-future (2046-2065) and long-future (2081-2100) MPI-ESM-LR RCP 8.5 driven simulations for the cell located within the Douro Superior sub-region. It can be observed that there are significant differences in the means in all cases except for DI between mid-term and long-term future. Regarding variances, only CI has significant differences between the mid-term and long-term future periods.

TABLE II. PRESENT AND FUTURE SCENARIOS FOR GRAPEVINE BIOCLIMATIC INDICES[a].

| | | MPIr | MPIm | MPIl |
|---|---|---|---|---|
| **HI (°C day$^{-1}$)** | μ | 1913** | 2401** | 2825** |
| | $\sigma^2$ | 32846 | 36466 | 37943 |
| **DI (mm)** | μ | 71** | -22** | -53 |
| | $\sigma^2$ | 4539 | 5126 | 5533 |
| **CI (°C)** | μ | 12,4** | 15,3** | 17,6** |
| | $\sigma^2$ | 1,2 | 2,7* | 1,1* |

a. * 95% significance level, ** 99% significance level

In Fig. 5, a HI shift is observed from temperate/temperate-warm conditions to warm conditions reaching even very warm conditions for some years in the long-future period.

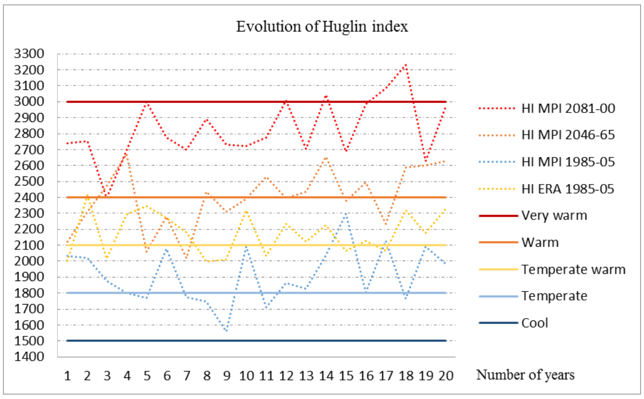


Fig 5. Evolution of Huglin index under ERA and MPI ESM-LR RCP 8.5 forcings.

In Fig. 6, a DI shift is observed from sub-humid to moderately dry and even very dry conditions for some of the years in the long-term future.

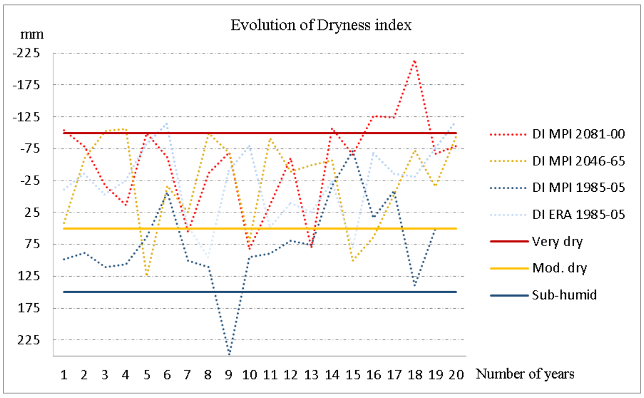


Fig 6. Evolution of Dryness index under ERA and MPI ESM-LR RCP 8.5 forcings.

In Fig. 7, a CI shift is observed from cool night to temperate nights even reaching warm-night conditions in the long-term future.

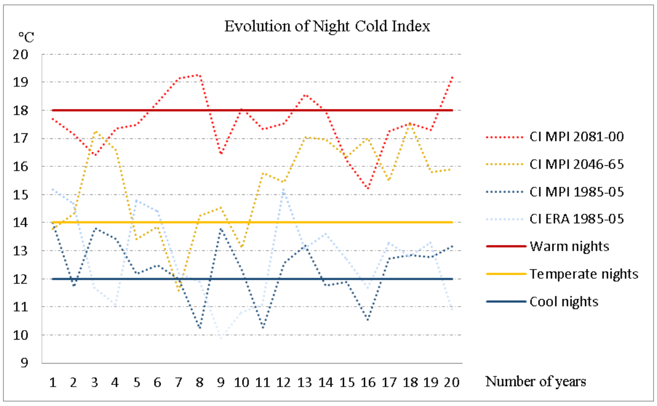


Fig 7. Evolution of Night Cold index under ERA and MPI ESM-LR RCP 8.5 forcings.

## V. Conclusions

The following conclusions can be drawn from this study:

- Climate MCC indices can be calculated from WRF-ERA and MPI simulations as a tool to assess the potential impacts of climate change on wine production.
- The mid and long-term future changes in climate in under the RCP 8.5 scenario reveal significant shifts to warmer and dryer conditions in the DDR as already warned in other GCM-RCM studies at the European and the Portuguese scale [5], [9].

Several actions can be proposed to preserve as much as possible DDR wine typicity taking current state-of-the-art knowledge [2] and previous work done in the study area [3]:

- Delay phenology by clonal selection, suitable rootstocks, and late-ripening local varieties or carefully selected non-local varieties.
- Training systems and late pruning can also be useful to delay phenology and reduce water deficit.
- Increase the soil water-holding capacity (SWHC) and select drought resistant rootstocks.
- Carefully assess the need for irrigation as it has an economic, environmental and social cost.

## Acknowledgment

The authors wish to thank the financial support of the DOUROZONE project (PTDC/AAG-MAA/3335/2014; POCI-01-0145-FEDER-016778) through the Project 3599 – Promoting the scientific production and the technological development, and thematic networks (3599-PPCDT) and through FEDER, and the national funds from FCT – Science and Technology Portuguese Foundation for the doc grant of C. Silveira (SFRH/BD/112343/2015).

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