ASSESSEMENT OF CLIMATE CHANGE IMPACTS ON WATER AVAILABILITY FOR VITIVINICULTURE WORLDWIDE USING DIFFERENT POTENTIAL EVAPOTRANSPIRATION METHODS

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Abstract:

Context and purpose of the study - Beyond the sole warming globally perceived and monitored, climate change impacts water availability. Increasing heatwaves frequency observed during the last decades and projected for the 21st century certainly result (or will result)in more water deficit stress for grapevine. Change in water availability throughout the season depends on the balance between precipitation and evapotranspiration. The latter is seldom assessed through potential evapotranspiration (ET_0) calculated with empirical formulae relying on air temperature only. This study compares the changes in water availability estimates for viticulture using such formulae in comparison to the reference Penman-Monteith approach.

Material and methods – Monthly interpolated minimum and maximum temperature, precipitation and Penman-Monteith (PM) ET_0 data for land surfaces worldwide were collected from the CRU TS4.01 gridded dataset, from 1971 to 2017. Other ET_0estimates were produced using the Thornthwaite (T) and the Hargreaves (H) temperature-based as well as the Modified Hargreaves (M) temperature-and-rainfall-based methods. PM, T, H, M ET_0 data were used to calculate the dryness index (DI), a monthly water balance-based index for viticulture. Changes between the periods 1971-2000 (HIST) and 2001-2017 (PRES) in potential evapotranspiration and in DI were compared for each of the 4 ET_0calculation methods. The changes were analyzed in wine producing regions using the vineyard geodatabase v1.2.3, a shapefile referencing 691 wine producing regions worldwide.

Results – All 4 methods compute an average increase (from HIST to PRES) in ET_0 of about 20 mm during the grapevine growing season, i.e. April to September (October to March) for the northern (southern) hemisphere. The change (PRES - HIST) differ substantially in space, according to the method used. For instance, a decrease in ET_0 is shown in southwestern and central North America when using PM method, while T method indicates a weak to moderate raise in ET_0 in these regions. Changes in dryness index from the late 20th to the early 21st century are large and highly variable in space: from -65 mm to +62 mm (0.05 and 0.95 percentiles), according to the location and to the ET_0 calculation method. DI also strongly varies in space, but results are less sensitive to ET_0 calculation method. PM shows a decrease in DI (PRES - HIST) down to -75 mm in most regions but Australia, central Europe and Italy. While PM, H and M methods indicate a clear decrease of DI in France, Portugal and Spain, T method suggests an increase in DI in the northern part of France and in most of Spain. It is concluded that (1) ET_0 has risen and contributed to DI decrease in many wine regions worldwide and (2) using T empirical method to derive ET_0 from temperature can lead to different conclusions concerning changes in water availability for viticulture.

Keywords: potential evapotranspiration, viticulture, climate change, temperature-based methods, dryness index

1. Introduction

Assessing water availability for crops requires to evaluate evapotranspiration, which measurement is complex. Therefore, many authors use reference (or potential) evapotranspiration (ET_0) to evaluate the evaporative demand of the atmosphere. The version of Penman-Monteith equation has been proposed in 1998 by the FAO (Allen et al., 1998) and became since then an international standard. It requires various climate variables as input, such as relative air temperature, air humidity, wind speed and solar radiation. However, temperature is the only of these input variables which is widely available in space and time. Therefore, several works addressing water scarcity for viticulture in a changing climate use temperature based estimates of ET_0(e.g. Paulo et al., 2012; Moriondo et al., 2013). As temperature has increased worldwide and as this rise is expected to continue in the future, temperature-based reference evapotranspiration increases as well, hence higher expected water scarcity. While ET_0 has indeed risen in some parts of the world such as France, Germany, Spain and Greece (McVicar et al., 2012;Schultz, 2019), the evaporative demand has declined in many parts of the world such as Russia, Australia, China, India and Israel during the end of the 20th century, possibly because of a wide spread terrestrial stilling (lower surface wind speed) trend roughly from 1960 to 2005 (McVicar et al., 2012). Such decline would probably not have been observed while using ET_0 estimates with temperature based formulas. Consequently, it can be expected that the use of the sole air temperature to assess change in evaporative demand might lead to flawed conclusions.

The current paper explores the consequences of using reference evapotranspiration calculated with temperature-based rather than the Penman-Monteith standard model for the assessment of water availability for viticulture during the growing season in wine producing regions worldwide, through the use of the dryness index (DI, Tonietto and Carbonneau, 2004). The spatial structures of the change in water availability between the early 21st century and the late 20th century assessed with 4 reference evapotranspiration methods are compared for non-tropical areas of the world, and then on wine producing regions only.

2. Material and methods

Climate data

As a primary data source, the Climate Research Unit (CRU, University of East Anglia) high resolution TS v4.02 dataset was used(Harris et al., 2014). The CRU TS dataset consists in a series of gridded data at monthly time step and at 0.5°x0.5° resolution. Its spatial extent covers the entire land surface of the planet. The 4.02 release provides data from 1901 to 2017. Amongst the variables available in this dataset, minimum temperature (TN), maximum temperature (TX), precipitation (P) and reference evapotranspiration (ET_0 calculated with the Penman Monteith FAO version model; Allen et al, 1998) monthly values were used, from 1971 to 2017.

Reference evapotranspiration and Dryness Index calculation

Four reference evapotranspiration formulae are compared: the Thornthwaite's method (T),the Hargreaves' temperature method (H)*,* the modified Modified Hargreaves' method (M) and the Penman-Monteith method.

T (Thornthwaite, 1948)uses average monthly temperature and day length (deduced from latitude and from the day of the year) to calculate monthly reference evapotranspiration. It's 1985 update by Willmott et al. (1985) has been widely used worldwide. I used this version in the present study.

H(Hargreaves and Samani 1982) uses minimum (TN) and maximum temperatures (TX) and top of the atmosphere irradiation (RA) to estimate reference evapotranspiration. In 2002, an updated version of the Hargreaves formulawas proposed (Droogers and Allen, 2002). It is referred to as Modified Hargreaves' equation. Mintegrates monthly P(in addition to TN and TX) and provides more accurate ET_0estimates for arid regions.

For PM calculation, the FAO version was used (Allen et al., 1998) in the CRU TS4.02 data set. It used air temperature, vapor pressure, cloud cover and 2 m wind speed as input variables. The CRU PM ET_0 was calculated using 1961-1990 averages. Hence, it does not account for the impact of wind speed on ET_0 changes over time.

Dryness Index (DI) – The Dryness Index is a proxy of water availability for viticulture accounting for the sole climatic conditions(Tonietto and Carbonneau, 2004). It is derived from the monthly water balance model proposed by Riou (1994) which separates grapevine transpiration from soil evaporation. The available soil water *W* is calculated each month *m* from April to September (October to March) in the northern (southern) hemisphere.DI is the available soil water on month 6 (i.e. September for the Northern Hemisphere and March for the Southern Hemisphere).

Precipitation, ET_0 and DI analysis for wine growing regions worldwide

Periods analyzed – Precipitation and ET_0 monthly values were cumulated during the growing season, i.e. April-September (October to March) in the Northern (Southern) hemisphere, so that periods during which DI, ET_0 and P were assessed are comparable. Growing season P and ET_0, as well as DI, of each grid cell were averaged for two periods: 1971-2000, defined here after as the recent past (hereafter referred to as HIST) period and 2001-2017 defined as the near present period (hereafter referred to as PRES). Difference between PRES and HIST are hereafter referred to as anomalies or ANOMS.

Spatial coverage of the study – P, ET_0 and DI were analyzed for extratropical land surfaces only, because the grapevine growing season period between the tropics generally differs from extra-tropical vineyards. A specific analysis was performed on non-tropical wine producing regions using the vineyard geodatabase (VGDB) v6.2.1. The VGDB consists in a set of polygons that delineates the areas either actually planted with wines (in Europe) or identified as wine regions within Atlases or other geodatabases(Bois et al., 2012).

3. Results and discussion

3.1. *Changes in evaporative demand and in dryness index according to the ET_0 model used*

Maps of growing season ET_0 anomalies (i.e. 2001-2017 ET_0 averages minus 1971-2000 ET_0 averages) for four evapotranspiration models are shown figure 1. While TET_0shows null to moderate changes in evaporative demand on most of the extra-tropical regions of the planet (> 8 mm for 95% of the 0.5°x0.5° grid cells), other methods exhibit higher diversity. In North America and Greenland, the spatial patterns of ET_0ANOMS strongly differ according to ET_0 method. PM methods suggest a decrease in the evaporative in demand in the southern part of Northwest America (e.g. southern California), in Central North America (e.g. Manitoba, Dakota, Nebraska States…) and in the northern part of Northwest America (e.g. Alaska and Canada's Northwest territories). In contrast, the modified Hargreaves method (M) suggest a decrease in Southeast USA. M model is driven by both temperature and rainfall. Consequently, the strong positive rainfall ANOMS in this region (e.g. more than 150 mm in Florida, results not shown) might be responsible for this overestimation of ET_0 increase in this part of the world.

The range in spatial variability of DI ANOMS are similar for each ET_0 model used. The largest range (0.05 and 0.95 percentiles) is found with M (-65 mm to +62 mm) and the narrowest amplitude is obtained with T (-52 to +50 mm). Contrarily to growing season ET_0 (as shown by Figure 1), spatial patterns of DI ANOMSare less sensitive to ET_0 input (when comparing T, H, M and PM models, results not shown). However, changes are noted in some areas of the world. For instance, PM-based DI anomalies decrease down to -75 mm in most regions but Australia, central Europe and Italy. In Europe, when considering PM, H and M ET_0, DIANOMS maps show a decrease in France, Portugal and Spain, while T-based DI ANOMSsuggests an increase in DI in the northern part of France and in most of Spain (results not shown).

3.2. *Climate-driven water availability for grapevine in wine regions*

I have extracted from the worldwide P, ET_0 and DI grids a subset of 809 grid cells which contained at least a wine producing area (as depicted by the vineyard geodatabase) which area was 1 km² or more. It corresponded to 390 wine producing regions. Grid cells were grouped by the so-called SREX references regions (Field et al. 2012) and the average pixels values for each region for PRES (2001-2017 period) P, ET_0 and DI and their anomalies (PRES - HIST) were calculated (table 1). In most wine regions, that change in P and ET_0 during the growing season was limited (less than 10% or PRES values) except for the growing season P in Southern Africa (SAF) which dropped by 31%. DIshowed stronger changes rising from 39 to 109 mm in Northern Australia, according to the method used. This increase in DI is surprising in this part of the world because during the growing season, precipitation has decreased and ET_0 has risen, which should have led to lower water availability. With lower precipitations, soil evaporation is reduced and might lead to lower deficit. A consequence of upper soil layers humidity which favours water loss and which is accounted for in DI calculation. In a similar manner, an increase in precipitation can lead to lower DI: a decrease in DI (from -11 to -25 according to the ET_0 model) was observed in West Asia, where rainfall as risen of 28 mm. These counter intuitive observations underline the interest of using a water balance modelling approach to assess the water offer by climate conditions rather than considering separately rainfall and potential evapotranspiration during a specific time of the year. In Southern Europe (MED) wine regions, DI anomalies are limited, while rainfall decreased (-11 mm) and ET_0 has risen. The decrease of rainfall was observed in southern France specifically in the first semester of the year (Brulebois et al. 2015). In MED, cloud cover has decreased in the late 20th century, specifically in the 1970s and 1980s (Sanchez-Lorenzo et al. 2017). This could explain the higher rise in PM ET_0 (+58 mm), in comparison to temperature based models ET_0 estimates.

4. Conclusions

This paper reports an analysis of extra-tropical P and ET_0 anomalies (early 21st century minus late 20th century averages) during the grapevine growing season and how they affected a water balance-derived index, the Dryness Index. According to the method used, the assessment of changes in ET_0 in time and space differ. Using different methods to calculate ET_0 have a limited impact in DI spatial structure assessment worldwide. However, trends differ at a regional scale. In Europe, different signs (increase or decrease) in DI anomalies were found. Their spatial distributions when using Thornthwaite's evapotranspiration method differed to those obtained with PM, H and M methods. Thornthwaite's method, in its 1985 most spread version, seems unsuitable to assess the evaporative demand, in comparison to other approaches.

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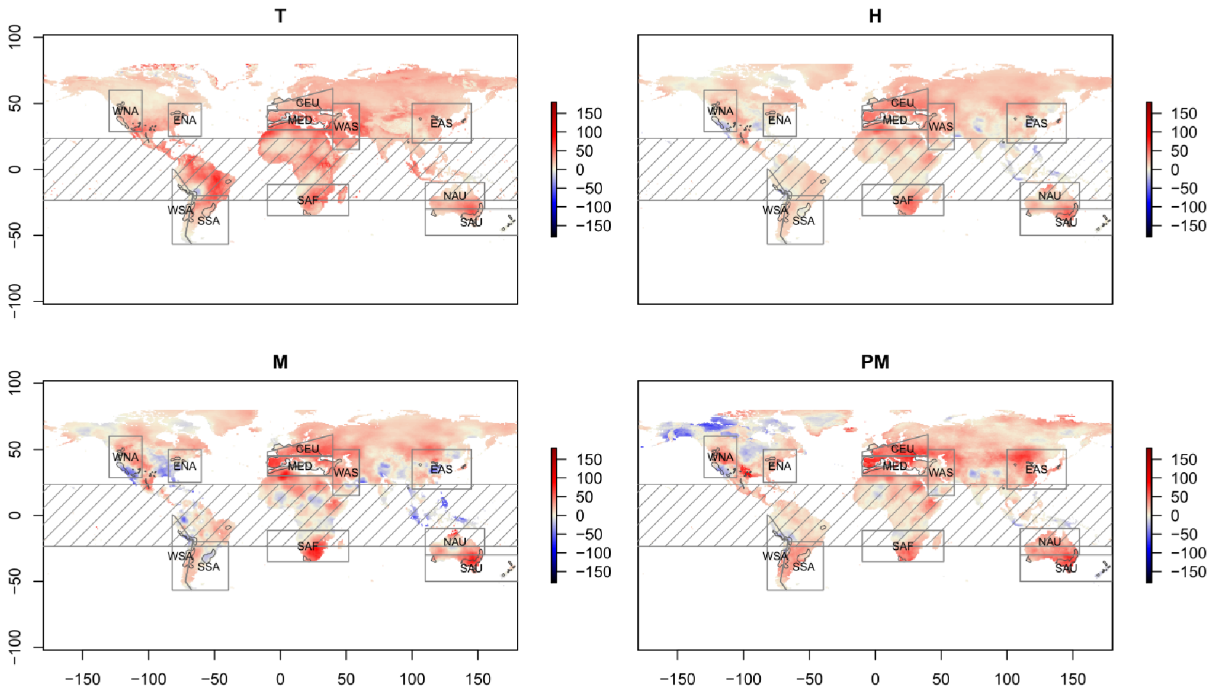

Figure 1: ET_0 anomalies (Difference PRES – HIST) for the growing season period defined as Apr-Sept (Oct-March) for the Northern (Southern) Hemisphere. Inter-tropical areas, where the growing season period might be different, are dashed. The colors indicate the value of ET_0 change in mm. Changes in ET_0 are presented for 4 different models: **(T)** Thornthwaite, **(H)** Hargreaves, **(M)** Modified Hargreaves, and **(PM)** Penman-Monteith. Gross locations of wine producing regions are delineated with a thin grey lines. Polygons with the 3 letters acronyms (see detail in table 1) refer to the so-called IPCC SREX regions, i.e. land reference regions used to analyze climate worldwide. Source data: CRU TS4.02 dataset.

Table 1: Average P, ET_0 and DI anomalies (numbers written in bold font) and PRES values (number in brackets, written in italic font) for wine producing areas in each SREX regions (see text and table 1 for details). SREX regions limits are drawn on Figure 1. N = number of CRU grid cell used for calculation, containing a wine region. Negative ANOMS are colored in red.

SREX Label	SREX reference region name	N	Precip.	Reference evapotranspiration				Dryness Index			
				T	H	M	PM	T	H	M	PM
WNA	**West North America**	94	**-12** *(141)*	**17** *(601)*	**-1** *(900)*	**-10** *(992)*	**7** *(892)*	**-6** *(3)*	**2** *(-113)*	**5** *(-160)*	**6** *(-106)*
ENA	**East North America**	23	**25** *(563)*	**18** *(590)*	**14** *(762)*	**10** *(728)*	**28** *(673)*	**-15** *(166)*	**-18** *(123)*	**-15** *(137)*	**-26** *(155)*
WSA	**West Coast South America**	39	**-3** *(80)*	**13** *(486)*	**15** *(818)*	**17** *(870)*	**22** *(779)*	**-23** *(25)*	**-20** *(-114)*	**-24** *(-141)*	**-26** *(-96)*
SSA	**South-eastern South America**	65	**27** *(568)*	**18** *(630)*	**7** *(926)*	**0** *(909)*	**24** *(852)*	**-7** *(127)*	**2** *(36)*	**5** *(29)*	**-12** *(52)*
CEU	**Central Europe**	150	**5** *(426)*	**29** *(588)*	**39** *(739)*	**47** *(724)*	**59** *(654)*	**21** *(155)*	**27** *(104)*	**31** *(109)*	**19** *(142)*
MED	**South Europe/Mediterranean**	292	**-11** *(230)*	**38** *(645)*	**32** *(843)*	**39** *(863)*	**58** *(840)*	**1** *(14)*	**5** *(-62)*	**7** *(-75)*	**-2** *(-60)*
WAS	**West Asia**	9	**28** *(371)*	**25** *(686)*	**22** *(911)*	**24** *(965)*	**14** *(876)*	**-20** *(-14)*	**-15** *(-91)*	**-19** *(-130)*	**-11** *(-77)*
SAF	**Southern Africa**	21	**-36** *(116)*	**21** *(581)*	**23** *(945)*	**33** *(1015)*	**51** *(1004)*	**-32** *(17)*	**-30** *(-144)*	**-36** *(-178)*	**-46** *(-172)*
EAS	**East Asia**	21	**-7** *(602)*	**19** *(612)*	**5** *(743)*	**0** *(669)*	**27** *(672)*	**7** *(151)*	**9** *(122)*	**11** *(128)*	**7** *(143)*
NAU	**North Australia**	2	**-24** *(498)*	**14** *(605)*	**23** *(963)*	**35** *(981)*	**37** *(1010)*	**39** *(178)*	**85** *(40)*	**109** *(45)*	**76** *(16)*
SAU	**South Australia/New Zealand**	93	**-20** *(308)*	**15** *(542)*	**25** *(865)*	**37** *(898)*	**36** *(865)*	**30** *(118)*	**31** *(-10)*	**36** *(-27)*	**24** *(-21)*