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# Water in a warmer world – is atmospheric evaporative demand changing in viticultural areas?

H.R. Schultz

Geisenheim University, von-Lade-Str. 1, 65366 Geisenheim, Germany

**Abstract.** The predicted developments in climate are region-specific and adaptation can only be successful considering the regional characteristics with its diverse technical, environmental, economic and social implications. One of the key concerns for many regions is the availability of water through precipitation, the distribution of precipitation throughout the year, and possible changes in evaporative demand of the atmosphere and thus water use. From rising temperatures it is mostly assumed that water holding capacity of the atmosphere will increase in the future as a function of the Clausius-Clapeyron law, which predicts an increase in the saturation vapour pressure of the atmosphere of 6–7% per degree Celsius. As a consequence, a simultaneous increase in potential evapotranspiration (ETp, the amount of water that could potentially be evaporated from soils and transpired by plants due to changes in climatic factors such as temperature, vapour pressure deficit, radiation and wind speed) is assumed in many cases, which would alter soil and plant water relations. However, the same underlying principles also predict an increase in precipitation by 1–2% per degree warming. Additionally, model predictions for many regions forecast altered precipitation patterns and thus in combination with the possibility of increased ETp, farmers around the world fear an increase in the likelyhood of water deficit and a reduction in the availability of water for irrigation. Contrary to expectations, there have been reports on a reduction in evaporative demand worldwide despite increasing temperatures. In many cases this has been related to a decrease in solar radiation observed for many areas on earth including wine growing regions in Europe until the beginning of the 80th (global dimming) of the last century. However, since then, solar radiation has increased again, but ETp did not always follow and a worldwide decrease in wind speed and pan evaporation has been observed. In order to evaluate different grape growing regions with respect to observed changes on precipitation patterns and ETp, the data of seven wine-growing areas in five countries in the Northern and Southern hemisphere across a large climatic trans-sect were analyzed (Rheingau, Germany, Burgundy, Rhone Valley, France, Napa Valley, USA, Adelaide Hills, Tasmania, Australia, Marlborough, New Zealand) were analyzed. Precipitation patterns differed vastly between locations and showed very different trends over observation periods ranging from 23 to 60 years. The ETp has increased continuously in only two of the seven wine growing areas (Rheingau and Marlborough). In most other areas, ETp has been stable during winter and summer for at least 22 years (Rhone Valley, Napa Valley, Tasmania), sometimes much longer (45 years Adelaide Hills), and has been declining in Burgundy after a period of strong increase for the last 13 years. The potential underlying factors are discussed in relation to observed shifts in precipitation patterns.

## 1. Introduction

Climate change effects on the terrestrial water cycle show regional differentiated patterns. While temperature is increasing in many world grape growing regions [1–5] precipitation patterns can vastly differ between regions and can show substantial temporal variations (between and within years) [6]. From rising temperatures it is mostly assumed that water holding capacity of the atmosphere will increase in the future as a function of the Clausius-Clapeyron law [7], which predicts an increase in the saturation vapour pressure of the atmosphere of 6–7% per degree Celsius. As a consequence, a simultaneous increase in potential evapotranspiration (the amount of water that could potentially be evaporated from soils and transpired by plants due to changes in climatic factors such as temperature, vapour pressure deficit, radiation and wind speed, ETp) is assumed in many cases, which would alter soil and plant water relations. However, the same underlying principles also predict an increase in precipitation by 1–2% per degree warming [8]. Additionally, model predictions for many regions forecast altered precipitation patterns and thus in combination with the possibility of increased ETp, farmers around the world fear an increase in the likelyhood of water deficit and the availability of water for irrigation.

However, the large spatial and temporal variability in precipitation patterns between regions preclude generalizations in predicted consequences with respect to soil and plant water status development. Especially the temporal variability may mask longer-term trends in the development of ETp and consequently soil and plant water status [9]. Additionally, the focus on the developments within a growing season (spring-summer) in many studies may miss decisive effects occurring during the "off-season" (winter-early spring) but having substantial carry-over effects into the season.

Evaporation is driven by changes in temperature, humidity, solar radiation and wind speed and contrary to expectations due to climatic changes, there have been reports on a reduction in evaporative demand worldwide [8]. In many cases this has been related to a decrease in solar radiation observed for many areas on earth including wine growing regions in Europe until the beginning of the 80th (global dimming, [10, 11]) of the last century. However, ETp in some areas has continuously increased which suggests that changes in the aerodynamic component must have more than offset the decrease in radiation over that part of the observed time span [12]. For some regions in Germany, wind speed and vapour pressure deficit (VPD) of the atmosphere have increased in the past and contributed to changes in evapotranspiration [13] but this is not in agreement with a worldwide observed decrease in wind speed and pan evaporation [8, 14].

These conflicting observations depending on climate classification, country or region, make it necessary to analyze grape growing regions with respect to developments in ETp and precipitation patterns much more in detail in order to make predictions with respect to an increased risk in terms of water shortage. There is a general lack of studies analyzing the past development in ETp and precipitation for different wine growing regions across the planet in order to answer the question whether the threat for sustained drought will increase. When ETp was set to increase in a future climate scenario, substantial reductions in pre-dawn leaf water potential resulted when a dynamic physiological grapevine water model was used [15] to estimate water consumption [16]. However, the large spatial and temporal variability in precipitation patterns between regions preclude generalizations in predicted consequences with respect to soil and plant water status development.

### 1.1. Water limited worlds versus energy limited worlds

Those parts of the earth where evaporative demand exceeds supply (rainfall), like many Mediterranean-type climatic regions, are very different from those parts of the world where rainfall exceeds evaporative demand, like for example Germany or many French grape growing areas. In the latter areas there is drainage to aquifers and runoff to rivers, and evaporation rate largely depends on the available energy and especially the radiation received. In water-limited regions, there is an excess of energy (e.g., solar radiation), and the actual evaporation rate can be close to the rainfall [8]. Grape growers from these different parts of the world have a very different view on their environment. The distinction between water limited versus energy limited worlds is not completely consistent because winters for example in water limited areas will, in many cases, be part of the energy limited "world" in Fig. 1 based on Budyko [17] and a conceptual analysis of Farquhar and Roderick [8]. Following this analysis, the actual evaporation rate, Ea, must be less than or equal to evaporative demand, ETp, and also less than or equal to precipitation, P (Fig. 1). The water-limited regions or the water limited part of the season (which could be part of both general areas) are on the left, and the energy-limited regions (or parts of the season) are on the right of the figure.

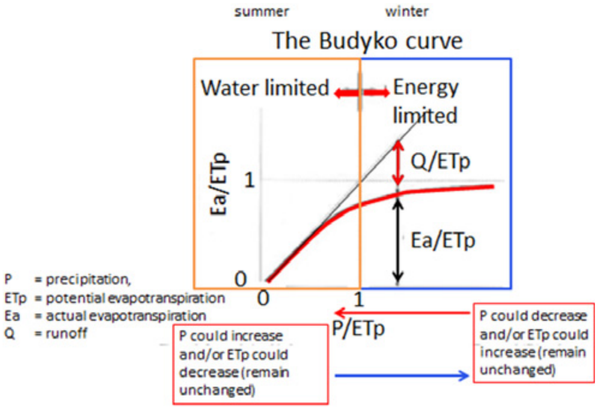

**Figure 1.** Inter-relationship between average precipitation (P), actual (Ea) and potential (ETp) evapo-transpiration and runoff (Q) and how season and climate change could affect this inter-relationship depending on the region. Grape growing areas are represented in both water and energy limited areas and the effect of climate change might be substantially different for different parts of the world. The original curve is known as the Budyko curve [17] and the presented figure is an adaptation from Farquhar and Roderick [8] in an extended version.

## 2. Material and methods

The base of possible changes in ETp is a change in temperature, which has been observed in many regions. In order to evaluate different grape growing regions with respect to observed changes on precipitation patterns and ETp and in order to validate or disproof general observations on changes across the planet [8], the data of five wine-growing areas in four countries in the Northern and Southern hemisphere across a large climatic transect were analyzed. Climate data for this analysis were provided by the German Weather Service (Deutscher Wetterdienst) for the location Geisenheim in Germany (50, 0° N, 8° E) in a temperate climate, the French INRA CLIMATIK, Agroclim project for the locations Dijon, Burgundy (47, 2° N, 5, 2° E), temperate climate, and Avignon (43, 9° N, 4, 9° E) in a Mediterranean climate for European wine regions. For overseas locations, the US California data provision system on integrated pest management provided data for Oakville, Napa Valley, CA (38, 3° N, 122, 3° W), a Mediterranean climate situation. The Australian Government, Australian Bureau of Meteorology, provided data for Williamstown, Adelaide hills (34, 7° S, 138, 9° E), a Mediterranean climate and Hobart, Tasmania, (42, 8° S, 138, 9° E), an oceanic climate and the Marlborough Research Centre, New Zealand delivered data for Blenheim, also an oceanic climate (41, 5° S, 173, 9° E).

Observational time series were different between locations and ended between 2015 and 2018. Data were seasonally separated into precipitation and ETp "summer" for the growing season (May-October for the northern hemisphere, October-May for the southern hemisphere), which in agro-meteorological terms is defined as the "hydrological summer" (Bormann 2011), and the "off-season" (November-April for the northern hemisphere, April-November for the southern hemisphere), the "hydrological winter". In the case of the German data, predictions for precipitation rates and ETp were used based on model-outputs of a regionalized version of the

STARII model of the Potsdam Institute of Climate Impact [18]. STARII constructs time series from 2007–2060 by resampling of observed weather data according to trend informations of the Global climate model ECHAM5/OM (A1B) [19]. This approach provides physical consistency of the combination of the weather variables and is in close agreement compared to the statistics of observed climatology [18].

## 3. Results and discussion

The general expectation, which is also very prevalent in the popular press, that as the world warms because of increased greenhouse forcing there will be a widespread increase in evaporative demand has been challenged by data proving the contrary and by a lack of scientific basis put forward by several scientists (see discussion [8]). Peterson et al. [20] were the first to publish the results from 190 sites in the former Soviet Union, where they found decreasing pan evaporation rates in the European sector, a decline in Siberia, and no trend in the Asian part. Since then many other reports from different parts of the world have been published but none has explicitly looked at grape-growing regions.

### 3.1. Observed and predicted summer trends for areas in Europe and California

Figure 2 (left panel) shows observed (calculated according to Penman-Monteith) and predicted changes in ETp during the growing season (May-October) for the temperate wine-growing region of the Rheingau (Geisenheim, Germany, 50.0° North, 8° East) from 1958 until 2060 [12]. To smooth out temporal variability, 10-year running mean values were used. There is a clear increase in the difference between ETp and precipitation rate during the growing season already observed during the past 55 years and this development will continue in the future as predicted using a regionalized version of the STARII model [18] (Fig. 2, left panel). A similar increase in ETp was also observed for the Mediterranean region near Avignon, France, since the mid-seventies of the last century, but with no observed change for about the last 20 years (Fig. 2, right panel). Available data for the Napa Valley in California show that ETp has not changed for approximately 30 years despite concomitant observations on rising temperatures.

Obvious from Fig. 2 (left panel) are the cyclic patterns of both ETp and precipitation rates, both for the period of observation and the projections until 2060. These cycles may be related to solar cycles which have been made partly responsible for the warming during the first half of the last century but not during the second half [21]. However, there is some uncertainty on whether these cycles do continue to have an impact on the temporal development of warming on earth and consequently on evaporation [21] but the data do show that variability and the development of extremes will become more likely despite cyclic variations (Fig. 2, left panel) [6]. These cycles have an important effect on how climate change is perceived by humans since they can somewhat mask long-term trends (when precipitation is increasing or ETp is decreasing for several years) or on the contrary suggest a speed-up in these trends (Fig. 2, left panel).

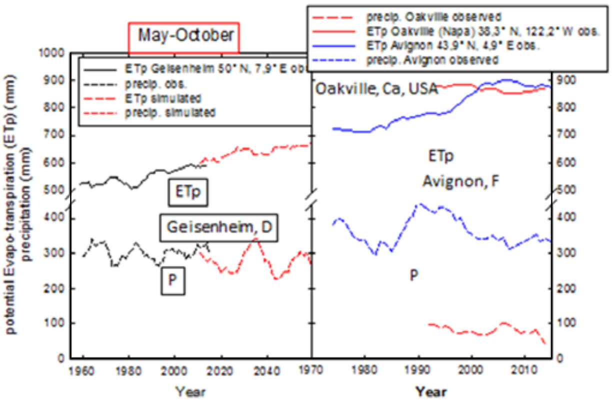

**Figure 2.** Observed and simulated precipitation and potential Evapotranspiration for the hydrological summer (May-October) for Geisenheim in the Rheingau region (Germany, 50° North; 8° East) (left panel). Potential Evapotranspiration rates for the observed time period (1958–2013) were calculated according to Penman-Monteith. Simulations were conducted with the STARII model of the Potsdam Institute of Climate Impact using the medium realization run [18] (adapted from Schultz and Hofmann [12]). In the right panel, observed ETp and precipitation data are shown for two Mediterranean type climate locations, one in Avignon, France, the other at Oakville in the Napa Valley, California. Data show 10-year running mean values. Observed data were from the Deutsche Wetterdienst, Germany, the French INRA CLIMATIK, Agroclim database and the US California data provision system on integrated pest management at the University of California, Davis.

Precipitation trends in Avignon have undergone some fluctuations but there was no distinct decrease observed, similar to summer precipitation in the Napa Valley, albeit on a much lower level (Fig. 3, right panel). If ETp predictions for the cool climate area of Germany (50° North) would be correct, then summer ETp values by the middle of the current century would be similar to Avignon (43, 9° North) in the seventies at lower precipitation rates.

### 3.2. Observed trends for Australian and California regions (summer and winter)

Analyzing data from one Australian region, Williamstown in the Adelaide Hills, it is obvious that neither ETp nor precipitation have changed substantially over the time period of available data confirming other data from Australian sites [22] (Fig. 3). The long-term data set from Williamstown shows that ETp decreased between the seventies and the nineties during both winter and summer before increasing again to the early ETp values. This might have been related to the phenomenon of global dimming, a reduction in solar radiation observed in many areas during that particular period caused by increased cloudiness and aerosols [10,11]. Precipitation rates also show no clear trend with a slight decrease during winter for the Adelaide Hills (left panel, Fig. 3). Similarly, ETp during winter and summer of the Napa Valley location did not change appreciably (Fig. 3), yet winter precipitation has almost been halved over the past 25 years, moving the area from an energy limited towards a water limited part on the Budyko curve (Fig. 1). Winter floods in 2017 have alleviated this somewhat and show that predictability of P is extremely limited. Despite of a "natural" focus on the

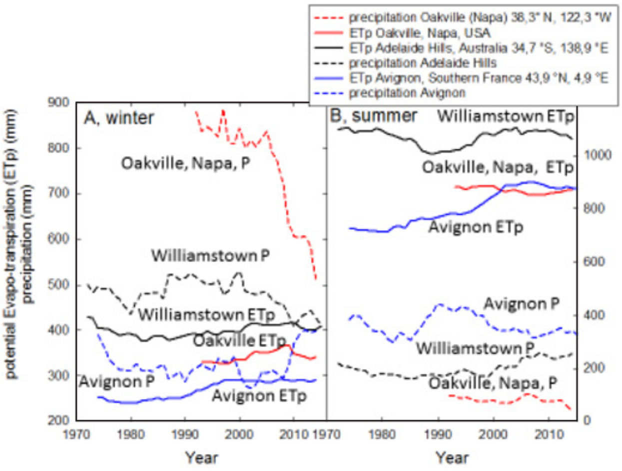

**Figure 3.** Observed precipitation and potential Evapotranspiration for the winter (left panel) and summer periods (right panel) for Oakville, Napa Valley, California (USA, 38, 3° North, 122, 3° West) and Williamstown in the Adelaide Hills (Australia, 34, 7° South, 138, 9° East). Avignon data from France have been added to illustrate how different regional situations are in broadly defined "Mediterranean climates". Data show 10-year running mean values. Observed data were from the US California data provision system on integrated pest management at the University of California, Davis and the Australian Bureau of Meteorology, Australian Government and the French INRA CLIMATIK, Agroclim database.

developments within the growing season, changes in the water budget during the "off-season" seem to become more important (Fig. 3 left panel). Regardless of the fact that during winter and spring precipitation rates are exceeding ETp, the "gap" between these two factors determining the soil water balance is decreasing in some areas [6]. This suggests that for this particular region winter precipitation will eventually be matched by winter ETp with important consequences for the amount of water stored in the soils at the beginning of the growing season. It may also have consequences for the use of cover crops during the winter.

The phenomenon that ETp remains stable or decreases in many regions even in the post-global dimming period has been related to different combinations of effects, yet the most pronounced effect seems that the wind speed in many areas has decreased [8]. A recent paper on the situation in China showed that wind speed has declined by 25–30% since the nineties [23] and a decrease of similar magnitude has been observed for the Cape region in South Africa [24] and are implicated in the worldwide decrease in evaporative demand [14]. Data on wind speed are not easily available, but over the same time period, wind speed has not changed in several German regions (data not shown) and in some even an increase has been observed [13], which could be part of the explanation of different trends for different areas.

### 3.3. Observed trends for cool climate regions in Germany and France (winter and summer)

Aside of Mediterranean-type, low summer rainfall climates (water limited) with a more or less continuous decline in water availability over most of the growing season, temporary water deficits also commonly occur in temperate, summer rainfall regions, specifically on vineyard sites with shallow soils and low water holding capacity (i.e., [9]). As compared to an irrigated vineyard situation in moderate or even hot climates, the natural cycles of stress and relieve can be much more pronounced albeit completely unpredictable in frequency, duration and severity in these areas and are naturally part of the 'terroir' and the year to year variation in wine quality. Most classic European grape growing regions are unirrigated and examples are given for two classical cool climate regions and the observed trends in ETp and precipitation during winter and summer (Fig. 4). Despite being classified as cool climate regions, both precipitation and ETp differ vastly. Geisenheim has higher ETp than Dijon in winter (Fig. 4a) and up to the nineties this was also the case for summer (Fig. 4b). Geisenheim shows a continuing increase in ETp over the past 60 years in both winter and summer, whereas Dijon in Burgundy showed a strong increase starting in the nineties for both winter and summer with no change or even a decline over the past 10–15 years during the summer months (Fig. 4b). Precipitation follows a cyclic trend in all regions and in all seasons with a strong decrease in winter precipitation in Dijon over the last 35 years (Fig. 4a). In general Precipitation and ETp are inversely correlated which would be according to theory [8].

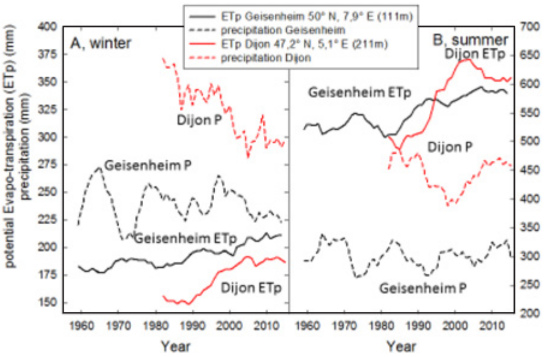

**Figure 4.** Observed precipitation and potential Evapotranspiration for the winter (left panel, A) and summer periods (right panel, B) for Geisenheim, Germany (50° North, 8° East) and Dijon, Burgundy, France (47, 2° North, 5, 1° East). Data show 10-year running mean values. Observed data were from the Deutscher Wetterdienst, Germany, and the French INRA CLIMATIK, Agroclim database.

## 4. Conclusions

The data show that generalisations with respect to global developments are not possible and that each individual region needs to be analysed with respect to observed trends and also with respect to expected developments [25]. The reasons for different developments in ETp seem to be complex and little understood. Trends might also be influenced by the drawing of moisture from water bodies which could balance the increases in temperature. According to the Budyko hypothesis, change in actual evaporation in dry regions is dominated by change in precipitation rather than potential evaporation. In humid regions, such as the cool climate examples given here, the change in actual evaporation is controlled by change in potential evaporation rather than precipitation, which would mean that the development of water deficit would become more likely in the future. Of all regions analysed, none has shown a continued decrease in ETp or an increase in precipitation as observed for other parts of the world [8]. Rising $CO_2$-concentration with its effect on stomatal closure and thus potential reduction in water use may also play a role in changes in the balance between precipitation and ETp [26].

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