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Beniston, Martin

How to cite

BENISTON, Martin. Exploring the behaviour of atmospheric temperatures under dry conditions in Europe: evolution since the mid-20th century and projections for the end of the 21st century. In: International journal of climatology, 2013, vol. 33, n° 2, p. 457–462. doi: 10.1002/joc.3436

This publication URL: <https://archive-ouverte.unige.ch/unige:18733>

Publication DOI: [10.1002/joc.3436](https://doi.org/10.1002/joc.3436)

Exploring the behaviour of atmospheric temperatures under dry conditions in Europe: evolution since the mid-20th century and projections for the end of the 21st century

Martin Beniston*

Institute for Environmental Sciences and Department of Physics, University of Geneva, Geneva, Switzerland

ABSTRACT: In a changing climate, it is likely that precipitation patterns will experience shifts in amount and seasonality, with a tendency towards increased drought in many parts of Europe. In order to investigate what could be some of the feedbacks of dry conditions on temperature, this paper has investigated close to 30 European locations to assess the influence of observed dry summer days on daily maximum temperature (T_{\max}) as well as a clustering of rainless days, and finally the temperature impact related to drought conditions as defined by the Standardized Precipitation Index. The results show that for the three main European climatic regions investigated ('Mediterranean', 'Maritime', 'Continental'), the influence of rainless days is discernible, with an average difference between mean summer T_{\max} and T_{\max} during rainless days only of up to 1.5 °C. A further aim of the study is to determine whether recent shifts in the occurrence of rainless days during the summer have a bearing on temperature trends. Results show that shifts in rainless days explain only a fraction of the observed temperature change at the locations studied, thereby hinting that the enhanced greenhouse effect remains the dominant mechanism for temperature change. Finally, using a regional climate model, very preliminary insight into a 'greenhouse climate' highlights the fact that changes in dry conditions seem to confirm the findings for current climate, i.e. they account for only a fraction of the increase in temperatures. Copyright © 2012 Royal Meteorological Society

KEY WORDS synoptic climatology; hydroclimatology; bioclimatology

Received 26 September 2011; Revised 15 December 2011; Accepted 16 January 2012

1. Introduction

The behaviour of temperatures in the lower atmosphere under dry conditions has been the focus of increasing attention in recent years. In many parts of the mid-latitudes, the intensity and persistence of heat waves have been shown to be closely linked to dry conditions – indeed, often prolonged drought – and soil moisture deficits, as shown *inter alia* by Seneviratne *et al.* (2006). More recent work by Jaeger and Seneviratne (2010) and Hirschi *et al.* (2011) has reinforced earlier conclusions on the links between dry soils and heat waves. Vautard *et al.* (2007) showed that European summer heat waves in certain parts of the continent may be triggered by drought in the Mediterranean region in the winter and early spring preceding the event. The dry conditions then often propagate northwards into Central and Western Europe in the summer months and tend to amplify the intensity and persistence of the heat wave.

Fluctuations in soil moisture are largely related to the seasonal and long term behaviour of precipitation, and also to water recharge in soils by rivers and lakes; surface

waters are themselves sensitive to precipitation amount and seasonality. It is, thus, of interest to explore the manner in which atmospheric temperatures during summer months are linked to the amount of precipitation, or lack thereof, and the possible spatial dependency in the temperature–precipitation relation for a number of European locations. Beniston (2009) already showed through an analysis of joint quantile distributions of temperature and precipitation that significant changes have been recorded in Europe in the course of the 20th century for particular combinations of cold or warm temperatures and low or high levels of precipitation, and that these changes would accelerate through 2100 in a 'greenhouse climate'. The paper also highlighted the implications of these temperature–precipitation mode changes for associated shifts in extremes such as heat waves, droughts, or heavy precipitation.

We seek to distinguish here between days without precipitation and drought, both of which will be addressed in this paper. Days without rain tend to be commonplace and, even in moist climates, can represent over 50% of summer days; clusters of days without rain help to differentiate between a short-term dry period (from a few days to a week or so) from drought conditions *per se*. In an overview paper, Dai (2011) defines drought as

* Correspondence to: M. Beniston, Institute for Environmental Sciences and Department of Physics, University of Geneva, Geneva, Switzerland. E-mail: Martin.Beniston@unige.ch

'a recurring extreme climate event over land occurring over a period of months to years'. There are a number of indexes that provide a quantification of drought; in this paper we shall use the Standardized Precipitation Index (SPI), introduced into the scientific literature by McKee *et al.* (1993) and discussed later by Guttman (1999).

The present paper seeks to explore the behaviour of temperatures as a function of three measures of dry periods, namely (1) the number of rainless days, (2) clusters of days without rain, and (3) SPI-defined drought at a number of locations in Europe, and the evolution of the temperature–drought relationships since the 1950s. A further aim is to have a first preliminary insight into the rainless day/temperature link in a scenario climate, using the results of a regional climate model (RCM). The objective here is not to conduct a suite of RCM experiments to obtain an ensemble-type of projections, however, but just to enable a first look at the future that can then be completed with a more exhaustive, model-based approach for a range of greenhouse-gas scenarios.

2. Data and methods

Almost 30 European sites have been selected for the statistical interpretation of temperature and precipitation data; the sites have been chosen as a function of the availability of daily data over long time scales (i.e. the 60-year period spanning 1951 through 2010) and their distribution within different climatic zones. The data for the European stations has been made available by the European Climate Assessment and Data (ECA&D, Klein Tank *et al.*, 2002). The data sets used have been quality-checked in terms of homogeneity in the records and continuity in the geographical location of the measurement stations.

In order to investigate the changes in a scenario climate, a suite of RCMs have been applied to simulate climatic conditions in Europe for the last 30 years of the 21st century in the context of the EU 'PRUDENCE' project; (Christensen *et al.*, 2002). The inter-model variability and the quality of model simulations have been reported *inter alia* in a special issue of *Climatic Change* (PRUDENCE 2007, Vol. 81). In the present investigation, the HIRHAM RCM of the Danish Meteorological Institute (Christensen *et al.*, 1998) has been used as it has shown skill in reproducing contemporary climate (Beniston *et al.*, 2007), thereby providing some measure of confidence for future climate simulations. The model has been applied to Europe at a 50-km resolution for both current climate simulations (the baseline 1961–1990 period), and one realization of a 'greenhouse climate' for 2071–2100, using the IPCC SRES A2 scenario (Nakicenovic *et al.*, 2000). The A2 scenario assumes a high level of emissions during the course of the 21st century, resulting in atmospheric CO₂ levels of about 800 ppmv by 2100 (i.e. roughly three times the pre-industrial values of CO₂).

Although it could be argued that using a single RCM is a major shortcoming of this paper, the idea here is not so much to provide a range of possible predictions of future changes, but rather to highlight a methodology that can be applied to both observed and simulated data. The approach discussed here would of course be applicable to all models in order to obtain an ensemble of possible futures; this is not the principle objective of the present paper, however.

In order to differentiate summertime (June–July–August or JJA) temperatures and their upper quantiles during rainless days, a straightforward method was used by which the temperature statistics were computed for all summer days (i.e. the 'average' conditions), and for just those days during which precipitation was less than 0.1 mm (i.e. 'dry' conditions). The difference between the 'dry' and 'average' conditions thus enables a quantification of the bias on temperatures associated with days without rain. Although the chosen precipitation threshold may be considered to be low for quantifying rainless days in a RCM, previous work with the HIRHAM model (Beniston, 2006) has shown that it is capable of reproducing reasonably well observed precipitation in the reference period 1961–1990. The 0.1 mm threshold is considered to be valid for this particular model, even if it may not hold good for all RCMs.

For the clustering of rainless days, the same analyses have been conducted for 4, 8, and 12 consecutive days without rain to see how the duration of a rainless event can influence the behaviour of temperatures. Finally, to assess the potential drought conditions on European temperatures, the SPI, was computed for a 1-, 3-, and 6-month period preceding each summer of the record. The SPI compares total cumulative precipitation at a given location for a specific time interval (e.g. the 1, 3, or 6 months used in this study) to the average cumulative precipitation for those same months for the entire length of the record. The SPI is thus a transformation of a time series of precipitation into a standardized normal distribution (Burke and Brown, 2008). Severe droughts are considered to occur when the SPI is less than -2 and very wet conditions when it is above $+2$, with normal conditions generally considered to be located within the interval -1 to $+1$.

3. Results and discussion

Figure 1 shows the distribution of ECA&D stations used in this investigation. The difference of maximum temperatures (T_{\max}) between dry summer days (T_{dd}) and all summer days (T_{jja}), hereafter referred to as ΔT_{dd} , and the number of rainless days per summer averaged for the 1951–2010 period are provided for each station. As seen in this figure, there are regional dependencies of rainless days and ΔT_{dd} that enables a classification of the selected stations into three broad climatic zones that can be referred to as (1) 'Mediterranean', (2) 'Maritime', and (3) 'Continental'.

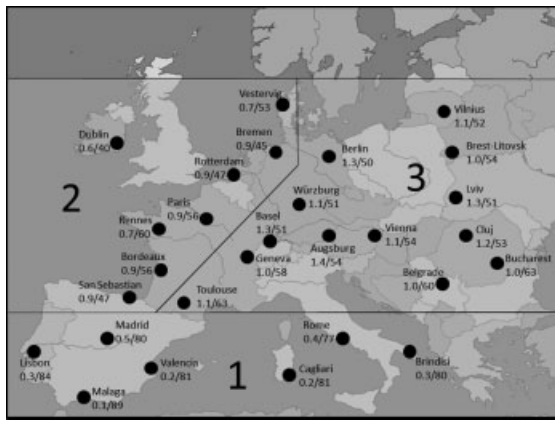


Figure 1. Map of Europe showing the location of the sampled sites, the three broad climatic zones into which they fall (1: Mediterranean, 2: Maritime, and 3: Continental), the average values of the difference in temperatures between dry summer days and all summer days (ΔT_{dd}), and the average number of rainless days per summer.

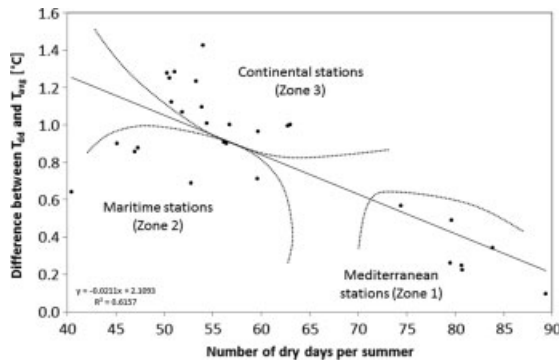


Figure 2. Relationship between the number of rainless days and the difference in temperatures between dry summer days and all summer days (ΔT_{dd}). The clustering of stations into the three broad climatic zone is provided on the diagram.

The Mediterranean summers are characterized by dry events in excess of 70 days, but where ΔT_{dd} values are constrained within a narrow range between 0.1 and 0.5. This is because the number of rainless days is close to the total number of summer days and, hence obviously, the temperature difference is low; in other words, for a location where all summer days would be rainless days, ΔT_{dd} would tend towards 0. The Maritime stations exhibit 50–65 rainless days per summer, with ΔT_{dd} around 0.8 ± 0.1 °C; in many Maritime locations, days without rain are not necessarily sunny days. Thus, cloud cover, for example, would be one feature in these zones that tend to limit atmospheric temperatures during days without precipitation. Continental locations (zone 3 in Figure 1) are associated between 45 and 60 rainless days per year; ΔT_{dd} values are close to 1 °C or more.

While a classification made on the basis of a rather limited number of stations can be open to question, Figure 2 shows that there is a reasonable degree of clustering within each climate regime. When looking at the relationship between the number of dry days and ΔT_{dd} at a particular location, the Mediterranean stations clearly stand out as a cluster in the bottom right portion of

Table I. Differences in mean summer T_{max} and T_{max} averaged over periods with 4, 8, and 12 consecutive days without rain, for the three principal climate zones discussed in this paper.

Climate zone	4 d	8 d	12 d
Mediterranean	1.2 ± 0.1	1.6 ± 0.2	1.8 ± 0.3
Continental	2.2 ± 0.2	2.9 ± 0.2	3.5 ± 0.1
Maritime	2.2 ± 0.9	3.2 ± 1.0	4.2 ± 1.0

the graph. Continental stations are located systematically above the regression line and Maritime stations remain systematically below.

The discussion up till now has focused on the number of rainless days summed for each summer. However, these can occur in the form of isolated dry days separated by periods of rainfall, and thus it is of interest to assess to what extent clustering of days with an absence of precipitation can influence the summertime T_{max} . Table I provides a measure of the difference between mean summer T_{max} (averaged for all summer days) and T_{max} averaged over clusters of 4, 8, and 12 consecutive days without rain, for the three climate zones defined above. The 1- σ spread of results between stations within the same zone is also given in Table I. It serves to highlight the fact that stations situated in the drier parts of Europe behave almost identically, while those in the Maritime locations have a greater spread, possibly because of more variable summer weather regimes close to the ocean than further inland or in the Mediterranean zone. The number of clusters of consecutive days without precipitation ranges from 3–6 episodes per summer for a 4-day threshold in the Maritime climates, and 0–2 episodes per summer for a 12-day threshold. For Continental stations, the 4-day threshold can occur between 4 and 6 times per summer, and the 12-day threshold occurs 0–2 times. In the Mediterranean locations, the essential part of the summer is dry so that there is little difference in ΔT_{dd} values, as previously mentioned.

Investigations of situations closer to genuine drought conditions, using the SPI, reveals that differences in temperature for periods where the index is below -1.0 , at which moderate droughts commence, are influenced by the tendency towards droughts for the 1-, 3-, and 6-month periods preceding each summer, as shown in Table II. As for Table I, the 1- σ spread is indicated to check whether there is consistency of values in each zone. The difference between T_{max} when $SPI < -1.0$ and average summer T_{max} ranges from 0.4 to 1.2 °C according to climatic zone (smallest difference in the Maritime zone and largest in the Continental set of stations), with a slight increase according to the duration of the period preceding the summer.

For the 60-year record considered in this study, all locations have experienced either increases or decreases in the number of rainless days and rising trends in both T_{jja} and T_{dd} . In all cases, temperature trends, computed through simple linear regression, are seen to be positive, whatever the location; temperatures over the

Table II. Differences in mean summer T_{\max} and T_{\max} averaged for SPI values below -1.0 (moderate drought), for 1-, 3-, and 6-month periods preceding each summer.

Climate zone	1 month	3 months	6 months
Mediterranean	0.8 ± 0.2	1.0 ± 0.3	1.0 ± 0.3
Continental	0.9 ± 0.3	1.1 ± 0.3	1.2 ± 0.3
Maritime	0.5 ± 0.2	0.6 ± 0.2	0.6 ± 0.2

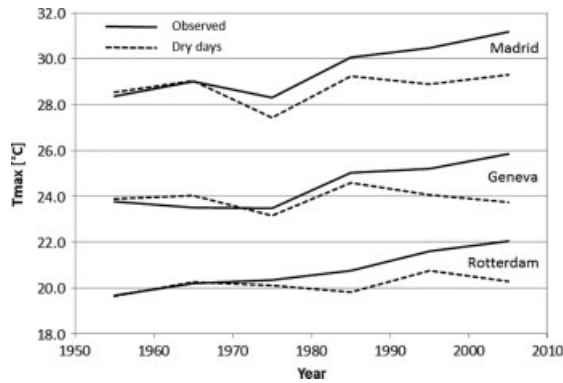


Figure 3. Solid lines: decadal-scale trends of summer maximum temperatures from 1951–2010. Dashed lines: evolution of summertime temperatures that would be expected when taking into account only the forcing by changes in the number of rainless days.

past 60 years have risen on average by 1.8°C for the 28 sites considered, with a $1-\sigma$ spread of 1.1°C . The largest increases are observed in the Mediterranean zone, with temperatures $3\text{--}4^{\circ}\text{C}$ at the end of the 60-year period compared with the beginning for Malaga, Spain, and Cagliari, Italy; the smallest increases over the 60-year record occur in the eastern part of the continent (Vilnius, Lithuania: $+0.4^{\circ}\text{C}$; Cluj, Romania: $+0.5^{\circ}\text{C}$).

The question here is to determine to what extent the changes in rainless days have driven the observed increases in diurnal summer T_{\max} since 1951. By looking at the shifts in temperatures for each incremental change in rainless days, it is seen that most Maritime locations experience an increase of maximum daily summer temperatures by about 0.15°C for each additional rainless day. This figure increases to around 0.2°C in Continental locations, and up to 0.5°C for Mediterranean stations. Figure 3 illustrates this point by showing the observed temperature curve and the trend that would have been observed if changes in rainless days were the only (or the dominant) factor influencing the 60-year evolution of temperatures, for selected locations within each of the three climatic zones (Madrid, Geneva, and Rotterdam, respectively). The data has been averaged for each decade of the record in order to remove the noisiness of inter-annual variability, and thus enables a highlighting of the long term trends. All curves exhibit a sharp rise in temperatures beginning in the 1970s and tailing off somewhat in the latter decade (2001–2010), with an overall 60-year increase of 2°C or more at these locations (similar results are seen for the other European sites sampled

in this study). The dashed curves have been computed by beginning with identical temperatures in 1951, and then adding incrementally the changes in temperature as a function of the changes in the number of rainless days (i.e. $0.2\text{--}0.5^{\circ}\text{C}$ per additional rainless day according to the climatic zone considered) from one year to the next. The dashed curves mimic to some extent the solid curves for the first two decades of the record, but rapidly diverge thereafter; 60-year changes in temperatures computed on the basis of dry-day forcing range from $+0.8^{\circ}\text{C}$ in Rotterdam and Madrid to -0.2°C in Geneva, where the number of rainless days has slightly declined since 1951. The discrepancy between the hypothetical dry-day curves and the observed warming reaches about 2°C at these locations (with similar results for the other sites, not shown here). Figure 3 thus suggests that rainless-day forcing alone does not explain the observed change in summer T_{\max} since 1951; indeed, in many locations where there have been decreases in rainless days (i.e. an increase in rainy days), such as Geneva, observed temperatures have risen at rates as large as in places where rainless days have increased. There are therefore obviously other and more dominant factors that explain the observed trends, among these certainly enhanced greenhouse-gas forcing (IPCC, 2007).

Because clustering of consecutive dry days, or prolonged drought tendencies have an influence on temperatures, the trends of consecutive days without rain and the SPI have also been computed in order to assess whether these trends may better contribute to observed warming than taking only the number of rainless days per summer into consideration. Table III illustrates for the same three stations as in Figure 3 the changes in the number of 4 and 12 consecutive dry days over the 60-year period, and also the changes in SPI for 1- and 6-month periods prior to each summer. All trends are significant at the 99% level with the exception of the 1- and 6-month SPI trends in Geneva that are very close to zero.

While the SPI analysis shows that there is a long term trend towards drier conditions seen in both the 1- and 6-month periods, there are contrasting trends in the consecutive rainless day trends, with slight increases or decreases according to location. The long-term summer temperature trends cannot therefore be attributed solely to

Table III. Trends in 4 and 12 consecutive rainless days (number of days for the 60-year record 1951–2010; negative figures imply less frequent rainless days), and for the Standardized Precipitation Index (change in the index over the 60 years; negative figures imply increasing drought) for Madrid, Geneva, and Rotterdam. Figures in italics (Geneva) indicate those trends that are not statistically significant at the 99% level of significance.

Location	4 d	12 d	1 month	6 month
Madrid	1.8	-1.1	-0.4	-0.7
Geneva	-1.5	-2.5	-0.1	-0.1
Rotterdam	1.0	0.7	-0.5	-0.5

changing rainless days or drought conditions. Regression analysis shows that temperatures increase by roughly 1.1 °C for each unit decrease of the SPI at the 1-month scale and by about 0.7 °C at the 6-month time scale, whatever the location and climatic zone considered. With the changes in SPI provided in Table III, a simple analysis suggests that the contribution of changing drought to summertime temperatures between 1951 and 2010 would be about +0.5 °C, thus representing only a fraction of the total observed warming.

The RCM simulations for the reference 1961–1990 climate show a reasonable agreement between observed and computed results at selected locations in each of the three broad climatic zones (Madrid, Geneva, and Rotterdam), acknowledging the fact that single-point observations in the real world are unlikely to be perfectly reproduced by the 50 × 50 km² grid-area values that the HIRHAM model grid-point represents. As seen in Table IV, simulated average summer temperatures (T_{jja}) are overestimated in both Madrid and Geneva (which is a feature common to many of the other Mediterranean and Continental stations), but are underestimated in Rotterdam; however, long term observed and simulated mean summer T_{max} are within 1 °C of each other. The number of dry days computed by the HIRHAM model is within ±10% of the observed, and ΔT_{dd} values are reasonably close to the recorded values.

Table V shows the results for the latter part of the 21st century when applying the RCM to the IPCC A2 scenario climate. Large increases in summertime diurnal temperatures are observed, ranging from 3–8 °C between the Maritime and Mediterranean sites. The number of dry days is seen to increase at all sites, from less than 5 in Mediterranean locations (which are already close to the maximum possible dry days under current climate), to about 10 in the Maritime stations, and between 12 and 20 in the Continental locations (16 in the case of Geneva, shown in this figure). It is particularly noteworthy to mention that there is no difference in ΔT_{dd} values between

the Control and the A2 simulations. The much warmer and generally drier summer climate in Europe does not amplify the influence of dry days on maximum summer temperatures, even though the future climate conditions will have a marked influence on other elements of the natural environment, in particular, surface and groundwater hydrology (Graham *et al.*, 2007).

By repeating the same procedure as for the results plotted in Figure 3, i.e. computing the temperature change that can be expected as a result of the change in the number of dry days, it is possible to calculate the temperature dependency of the increase in the number of dry days between current and future climate for this particular model. Figure 4 shows that the change in dry days explains only part of the increase in temperature through the end of this century (i.e. 2 °C of 7 °C projected warming in Madrid, 1 °C of 4 °C in Rotterdam, and 2 °C of 6 °C in Geneva). Increases in computed temperatures based on dry-day trends suggest an increase of 2–3 °C according to region, compared with 4–8 °C simulated by the RCM. The potential positive feedback effect of days without rain on summertime temperatures is thus

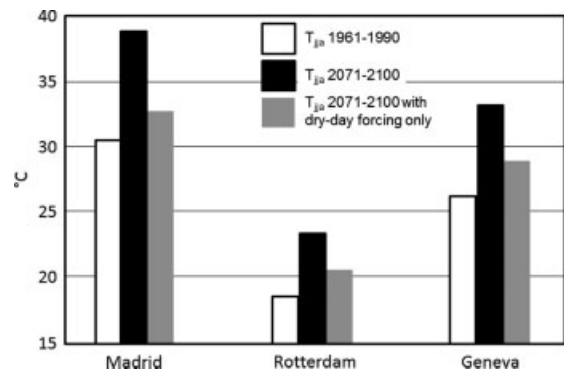


Figure 4. Simulated summer maximum temperature for the reference control period, for the IPCC A2 scenario climate, and the temperatures that would be expected when taking into account only the forcing by changes in the number of rainless days.

Table IV. Comparisons between observations and model simulations for the reference period 1961–1990 in terms of the number of dry days per year, average summer maximum temperatures, the difference in temperatures between dry summer days and all summer days (ΔT_{dd}).

Location	Dry days (obs.)	Dry days (model)	T_{max} (obs.)	T_{max} (model)	ΔT_{dd} (obs.)	ΔT_{dd} (model)
Madrid	87	85	29.4	30.2	0.5	0.3
Geneva	57	62	24.5	25.8	1.0	0.9
Rotterdam	54	57	19.6	19.0	0.9	0.6

Table V. Comparisons between model simulations for the reference period 1961–1990 (CTRL) and the 2071–2100 scenario climate (A2) in terms of the number of dry days per year, average summer maximum temperatures, the difference in temperatures between dry summer days and all summer days (ΔT_{dd}), and the differences between A2 and CTRL for T_{max} and ΔT_{dd} .

Location	Dry days (CTRL)	Dry days (A2)	T_{max} (CTRL)	T_{max} (A2)	ΔT_{dd} (CTRL)	ΔT_{dd} (A2)	Δdd	ΔT_{max}	$\Delta(\Delta T_{dd})$
Madrid	85	88	30.2	38.9	0.3	0.2	3	8.7	–0.1
Geneva	62	78	25.8	32.8	0.9	0.9	16	7.0	0.0
Rotterdam	57	69	19.0	23.2	0.6	0.6	12	4.2	0.0

marginal compared with the dominant influence of the enhanced greenhouse effect.

These findings do not include the additional feedback effects that would be expected from progressively drier soils that an increase in dry days imposes upon the system, however. This study has highlighted just the first-order effect of rainless days in summer on daily T_{\max} to emphasize the fact that rainless conditions alone represent a relatively minor amplification factor on summertime temperatures compared with other – and sometimes related – mechanisms.

4. Conclusions

This paper has reported on the behaviour of maximum diurnal summer temperatures (T_{\max}) during rainless days compared with the average summer T_{\max} . It is seen that for much of Europe, the ‘signature’ of ΔT_{dd} enables a classification of climate recording stations into three broad climatic regimes. Changes in rainless days over the course of the investigated period (1951–2010) are seen to influence T_{\max} , but these shifts explain only partially the large increases in average summer T_{\max} observed at all stations sampled; indeed, T_{\max} is seen to increase by over 2 °C during the 60-year record even at locations where the number of rainless days has decreased. Even if dry/drought conditions are instrumental in determining temperatures, sometimes in a heat-wave mode, at a particular location and according to the persistence of the event, their evolution over the course of the last 60 years has contributed in a fair, but not dominant, manner to the observed increase in T_{\max} .

RCM predictions show that the increases in dry days that are projected for all the sampled sites in Europe likewise contribute to some extent to the overall increases in T_{\max} by 2100. This probably highlights the dominant role of the enhanced greenhouse effect during the course of the 21st century over other climate drivers; even if prolonged droughts as projected by RCMs are likely to enhance the upper range of T_{\max} well beyond current values in the future, the average ΔT_{dd} values remain essentially unchanged between the current and scenario climates (i.e. T_{jja} and T_{dd} values increase by roughly the same amounts in the scenario climate).

Further work on this topic will thus entail an investigation of these issues for a ‘greenhouse climate’, using the results of more than just the one RCM used here (recognized as a limitation to the present study), where these analyses will be repeated to determine whether the relationship between future summer temperature and rainless/dry/drought conditions will change significantly, and under which carbon emissions scenario.

Acknowledgements

This work has been in part supported by the Framework Programme 7 R&D project ‘ACQWA’ (www.acqwa.ch) of the European Union, under Grant Number 212250.

Thanks are extended to the anonymous reviewers who helped improve the contents of the manuscript.

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