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Observational evidence for soil-moisture impact on hot extremes in southeastern Europe

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Climate change is expected to affect not only the means of climatic variables, but also their variabilities[1,2] and extremes such as heat waves[2–6]. In particular, modelling studies have postulated a possible impact of soil-moisture deficit and drought on hot extremes[7–11]. Such effects could be responsible for impending changes in the occurrence of heat waves in Europe[7]. Here we analyse observational indices based on measurements at 275 meteorological stations in central and southeastern Europe, and on publicly available gridded observations[12]. We find a relationship between soil-moisture deficit, as expressed by the standardized precipitation index[13], and summer hot extremes in southeastern Europe. This relationship is stronger for the high end of the distribution of temperature extremes. We compare our results with simulations of current climate models and find that the models correctly represent the soil-moisture impacts on temperature extremes in southeastern Europe, but overestimate them in central Europe. Given the memory associated with soil moisture storage, our findings may help with climate-change-adaptation measures, such as early-warning and prediction tools for extreme heat waves.

A preferential warming of the hot tail of temperature distributions as a consequence of climate change has been reported in observational studies for the European continent, where changes in the upper and lower tails of daily minimum, maximum and mean temperature distributions have been analysed[14–16]. Strong trends in heat-wave intensity, length and number have in particular been identified in the eastern Mediterranean region[17]. In the context of modelling studies, soil moisture has been shown to possibly play an important role for the occurrence of hot extremes in Europe[7,10,11] and impending changes thereof with climate change[7,8,18].

Using quantile regression[19,20] (see Methods), we investigate whether such a relation between dry conditions and hot extremes can indeed be established from observations in Europe based on a newly available observational database. Quantile regression was developed as an extension to the ordinary least squares regression to estimate the response not only in the mean of a variable, but in all parts of its data distribution. It has been widely used in econometrics[19,20], and in some ecological studies[21]. Recently, the method has been applied for the identification of trends in the Baltic sea level[22].

For the analysis, we use the standardized precipitation index (SPI; ref. 13, see Methods), a commonly used drought index[23,24], and two temperature indices from the CECILIA climate and extreme database (see Methods): the percentage of hot days (%HD) and the maximum heat-wave duration ($\mathrm{HWD}_{\mathrm{max}}$). This database was developed in the framework of the EU-FP6 project CECILIA and provides indices computed from two observational sources: (1) the gridded E-Obs dataset[12] and (2) high-density station data from the participating institutions (Fig. 1). The latter set of indices represents an invaluable new observational reference for the investigation of extreme events in central and

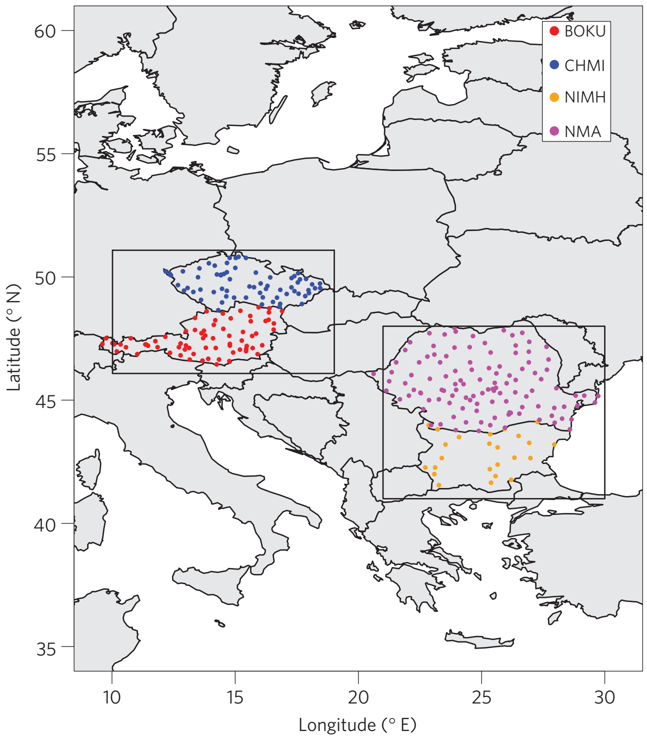

Figure 1 | Station observations and analysis domains. Location of high-density station observations from the CECILIA climate and extreme database (responsible institutions: University of Natural Resources and Life Sciences (BOKU), Austria; Czech Hydrometeorological Institute (CHMI), Czech Republic; National Institute of Meteorology and Hydrology (NIMH), Bulgaria; National Meteorological Administration (NMA), Romania), as well as analysed central and southeast European domains (boxes).

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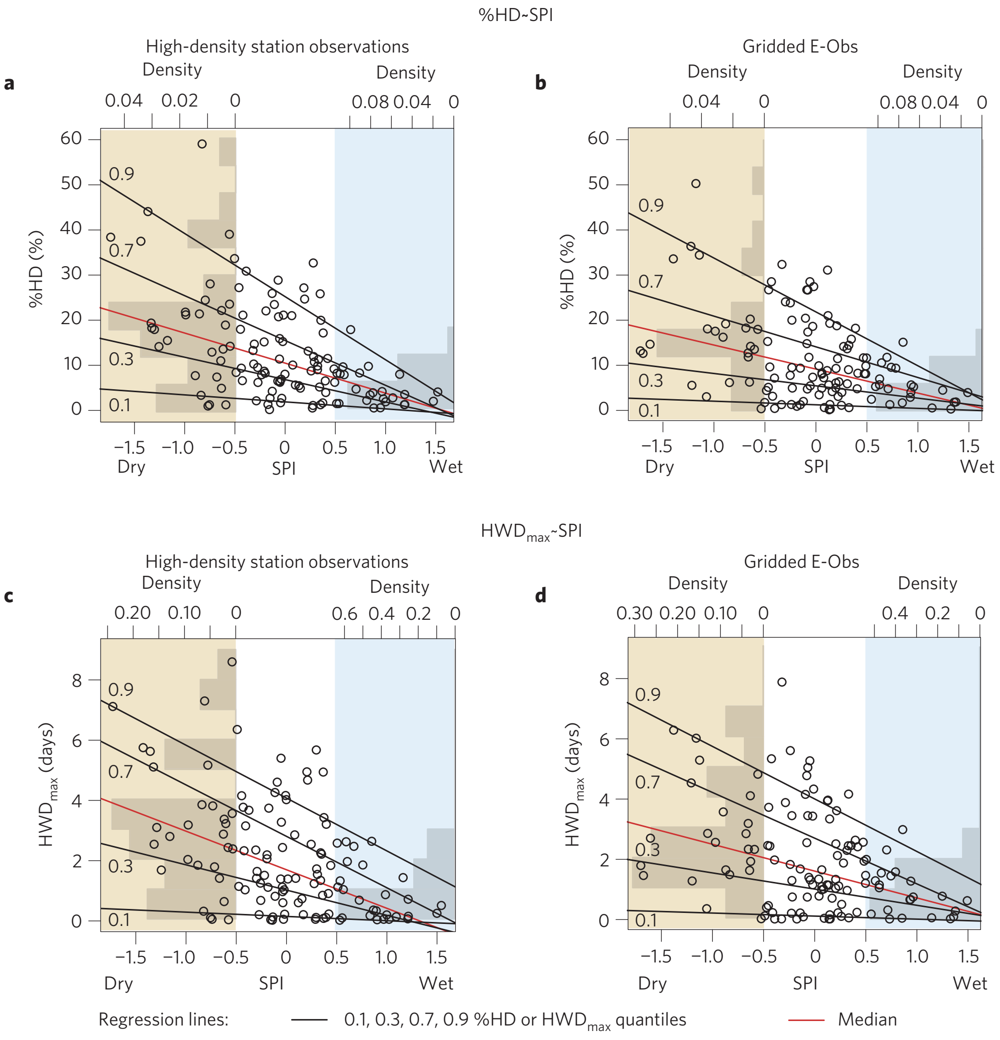

Figure 2 | Hot extremes versus SPI. a–d, Scatter plots of monthly JJA %HD (**a**,**b**) and HWD_{max} (**c**,**d**) versus SPI from the high-density station observations (**a**,**c**) and from the gridded E-Obs dataset (**b**,**d**), based on domain-averaged values for the southeast European domain (1961–2000 period). Also shown are histograms of the probability density for wet and dry conditions respectively, as well as the regression lines for a selection of distinct quantiles (that is, median, 0.1, 0.3, 0.7, 0.9). For 95% confidence intervals of the slopes of the quantile regression lines, see Fig. 3.

eastern Europe. Moreover, computed indices from reanalysis-driven regional climate model simulations (see Methods) are also included in the analysis.

The central and east European CECILIA target region is divided into two domains for the analyses (see Fig. 1): a southeast European domain (21° –30° E, 41° –48° N) situated in a transitional soil-moisture regime[25] (soil-moisture-limited evapotranspiration regime)[26], and a central European domain (10° –19° E, 46° –51° N) with wet soil-moisture regime (energy-limited evapotranspiration regime)[26]. It is thus expected that the effect of soil moisture on hot extremes is stronger for the former of the two domains[7,27] (see Methods for details). The station- and grid-point-based temperature indices and SPI are averaged respectively over these domains for the analyses (see Methods).

Figure 2a–d shows scatter plots of monthly June–July–August (JJA) data of %HD and HWD_{max} versus SPI from the high-density station observations and from the gridded E-Obs dataset averaged over the southeast European domain (1961–2000 period, $n = 120$). In these panels, histograms of the probability density are shown for wet and dry conditions respectively, together with the regression lines for a selection of distinct quantiles (that is, median, 0.1, 0.3, 0.7, 0.9; see Methods for the derivation of the slope and intercept parameters β_τ and γ_τ of the quantile regressions). This analysis reveals a widening of the %HD and HWD_{max} data distributions with drier conditions. This is also apparent in the gradually increasing negative slopes of the quantile regression lines towards higher %HD and HWD_{max} quantiles. Hence, we indeed find an intensification of hot extremes with drier surface conditions in the domain with transitional climate and soil-moisture regime. The corresponding scatter plots with data points coloured according to different ten-year time periods can be found in Supplementary Figs S1 and S2 for both domains.

To investigate this relationship further and to identify how different temperature indices are affected by moisture availability as a function of the soil-moisture regime, we show in Fig. 3 respective quantile regression slopes for the two mentioned temperature indices in the southeast versus central European domains. These analyses are shown for the two sets of observational indices (based on station data and the gridded product) as well as for the considered reanalysis-driven regional climate simulations. For the observations, the 95% confidence intervals of the estimated slopes are also shown as shading. These have been derived using a pairwise block bootstrap (with non-overlapping blocks consisting of the three consecutive summer months of each year so as to take into account the intra-annual autocorrelation of the data). Significant slopes (5% significance level, two-tailed test) are

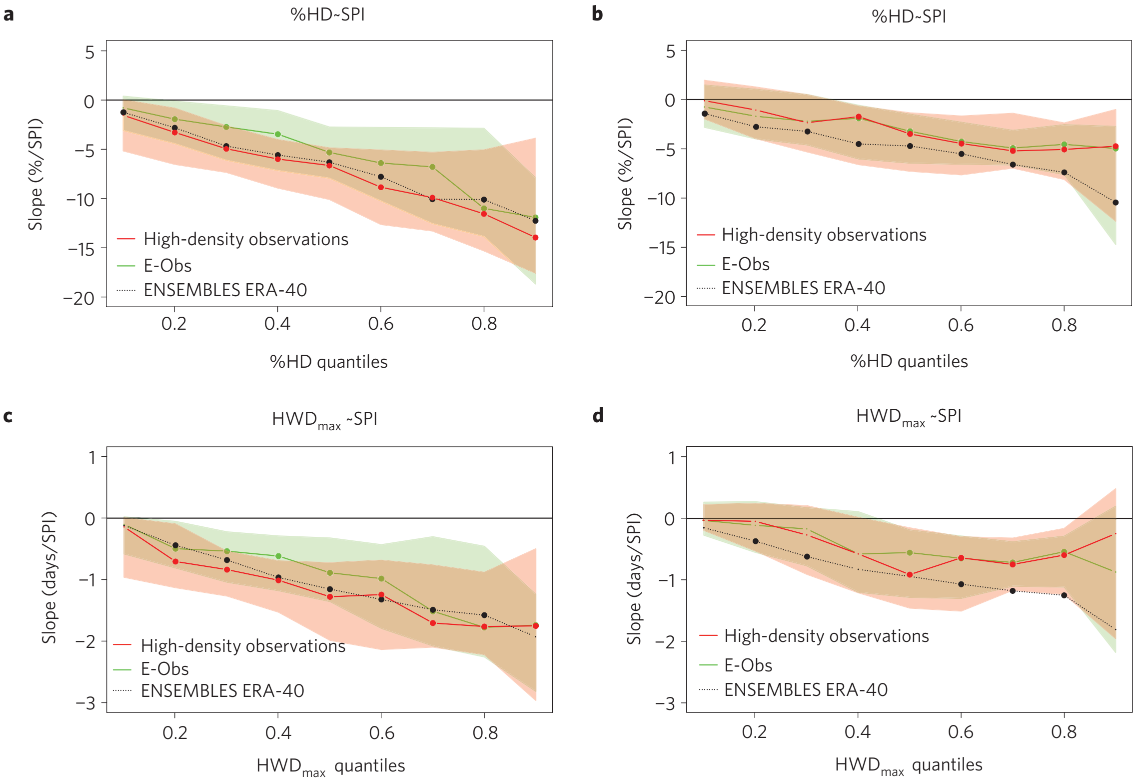

Figure 3 | Quantile regression analysis. Quantile regression slopes of the 0.1–0.9 quantiles of monthly JJA %HD and HWD$_{max}$ in relation to SPI for the two observational datasets and for the reanalysis-driven regional climate model simulations (1961–2000 period, southeast (**a**,**c**) and central (**b**,**d**) European domains). The 95% confidence intervals of the estimated slopes are shown as shadings for the observational datasets, with significant slopes denoted with a bold dot (5% significance level, two-tailed test). For the model simulations, the ensemble median slopes are shown, and dots are shown as bold when at least 75% of the simulations present significant slopes.

highlighted with bold dots. In the case of the regional climate model simulations, the ensemble median slopes are shown, and dots are shown as bold when at least 75% of the individual models present significant slopes.

Figure 3a,c shows the respective quantile regression slopes of the 0.1–0.9 quantiles of %HD and HWD$_{max}$ in relation to SPI in the southeast European domain, that is, corresponding to the analysis of Fig. 2. As in Fig. 2, gradually increasing negative slopes for increasing %HD and HWD$_{max}$ quantiles are identified from the observational datasets. The strong relation of upper quantiles of %HD and HWD$_{max}$ with SPI is found to be a robust feature on both monthly (Figs 2 and 3) and seasonal (Supplementary Fig. S3a,c) timescales, as well as for different tested time periods (Supplementary Fig. S4). The inferred slopes are similar for the high-density station observations and the gridded dataset, but slightly more pronounced and significant for the former.

By contrast, only a weak relationship between SPI and the analysed temperature indices is identified in the central European domain (Fig. 3b,d), which is generally insignificant on the seasonal timescale (Supplementary Fig. S3b,d). In that domain, the relations of the quantiles of %HD and HWD$_{max}$ with SPI also do not present a clear tendency with increasing quantiles. Thus, the soil-moisture regime indeed seems critical in explaining the identified relationship between SPI and the temperature extremes in the two investigated regions, consistent with theoretical considerations[27].

This is further illustrated in Table 1, which lists the median and 90th percentile %HD and HWD$_{max}$ values as a function of SPI for the two domains (based on the regressions shown in Fig. 2 and the Supplementary Fig. S1 for the high-density station observations). A stronger relationship of the extreme quantiles of %HD and HWD$_{max}$ with SPI in the southeast versus central European domain is again clear from this summary. Distinct relationships for median and 90th percentile values in the southeast European domain are also confirmed. In southeast Europe, the percentage of hot days increases from 4.5% to 43% for the 90th percentile values, respectively from 1% to 19% for median values, in the case of (moderate-to-severe) drought versus wet conditions. The maximum heat-wave duration is also significantly impacted, with an increase from 1.2 to 6.9 days for the 90th percentile values, respectively from 0 to 3.3 days for the median values. For the central European domain, only weak tendencies are found between dry versus wet summers, and in particular no clear discrepancies are found for the relationship of extreme quantiles versus median values with SPI.

Do current climate models correctly represent the impact of drought conditions on hot extremes in central and eastern Europe? On the basis of the analyses in Fig. 3 and Supplementary Fig. S3, the investigated ERA-40-driven regional climate model simulations from the European ENSEMBLES project seem to capture the identified relationship in the southeast European domain, but overestimate the impact of moisture deficit in the central European domain, in particular on the seasonal timescale. Thus, while they are able to represent the respective relationships to some extent, the geographical delimitation of the soil-moisture regimes (and respective evapotranspiration regimes) does not seem to be fully correct for the present climate, at least for the models' mean behaviour. Hence, it is possible that currently available regional climate projections do not correctly estimate the projected risk of heat-wave occurrence in central Europe.

Another relevant question is the extent to which recent trends in drought occurrence may have impacted reported trends in the occurrence of hot extremes. Supplementary Fig. S5 shows the

Table 1 | Median and 90th percentile %HD and HWD$_{max}$ values (including their 95% confidence intervals) as a function of SPI for the two domains.

High-density station observations		%HD (%)		HWD$_{max}$ (days)	
		Median	90th percentile	Median	90th percentile
Southeast European domain	SPI = −1.5 (moderate-to-severe drought)	19 [11, 26]	43 [29, 57]	3.3 [1.5, 5.0]	6.9 [3.5, 10.3]
	SPI = −1 (mild-to-moderate drought)	16 [10, 22]	37 [25, 48]	2.7 [1.4, 4.0]	6.0 [3.4, 8.5]
	SPI = 0 (normal conditions)	10 [7, 13]	24 [17, 31]	1.6 [1.0, 2.3]	4.1 [2.8, 5.3]
	SPI = 1 (mildly-to-moderately wet)	4 [1, 7]	11 [9, 13]	0.5 [−0.3, 1.3]	2.2 [0.4, 3.9]
	SPI = 1.5 (moderately-to-severely wet)	1 [−4, 5]	4.5 [4, 5]	0 [−1.2, 1.1]	1.2 [−1.3, 3.7]
Central European domain	SPI = −1.5 (moderate-to-severe drought)	16 [7, 24]	28 [−1, 57]	3.0 [1.1, 4.8]	4.5 [0.7, 8.3]
	SPI = −1 (mild-to-moderate drought)	14 [7, 20]	26 [3, 48]	2.5 [1.1, 3.9]	4.3 [1.4, 7.2]
	SPI = 0 (normal conditions)	10 [7, 14]	21 [9, 33]	1.6 [0.9, 2.4]	3.8 [2.3, 5.3]
	SPI = 1 (mildly-to-moderately wet)	7 [4, 10]	16 [4, 29]	0.7 [−0.3, 1.7]	3.4 [1.3, 5.5]
	SPI = 1.5 (moderately-to-severely wet)	5 [1, 9]	14 [−3, 31]	0.3 [−1.1, 1.7]	3.1 [0.2, 6.0]

The values are based on the regressions shown in Fig. 2 and the Supplementary Fig. S1 for the high-density station observations.

temporal evolution of seasonal (JJA) mean %HD, HWD$_{max}$ and SPI (that is, $n = 40$) for the station observations and E-Obs in southeast Europe. The applied non-parametric Wilcoxon–Mann–Whitney (test for a shift in location between 1961–1980 and 1981–2000) and Mann–Kendall (test for monotonic trends, applied after 1970) tests indicate a significant increase, respectively decrease, of the hot extremes and SPI over the investigated time period (5% significance levels, two-tailed tests, with corresponding p values in the panels). Together with the observed relation of the temperature extremes with SPI identified in Figs 2 and 3, this suggests that part of the observed trend in the hot extremes could have resulted from trends in moisture availability. We can infer from the station observations that this result is not the fortuitous consequence of parallel trends in SPI and temperatures, because a significant relation between the two investigated temperature indices and SPI is also found for temporally de-trended data (Supplementary Fig. S6). In the case of the gridded dataset a widening of the confidence bands is seen, which may be due to the lower density of the underlying observational basis.

This observational study partly supports previous modelling results suggesting an amplification of temperature extremes by soil-moisture state in Europe in the context of global warming and linked with geographical characteristics of soil-moisture regimes[7,27]. This amplification is found to be most pronounced for the hot tails of the temperature extremes' distributions. Climate models are found to overestimate this relationship in central Europe, while they agree well with observations in southeast Europe. This has important implications for model-based analyses and projections of hot extremes in Europe and other regions[2,3,5–10].

As climate change is expected to further enhance summer drying in Europe[7], the observed relationship between SPI and hot extremes implies a further amplification of the latter in coming decades. For the correct representation of these changes, models will need to be constrained by observations to better capture regions of soil-moisture impacts on hot extremes. This is also relevant for adaptation measures, in particular for the successful development of early warning and prediction tools for these extremes[28]. Indeed, the importance of soil moisture for hot extremes implies an enhanced predictability of such extremes, given the persistence associated with soil-moisture storage.

Methods

Quantile regression. In classical linear regression, the conditional mean of a response random variable Y is modelled as linearly related to a random variable X, that is,

$$E[Y|X] = \beta X + \gamma = f_{(\beta,\gamma)}(X)$$

with β denoting the slope and γ the intercept. The parameters β and γ are estimated by minimizing the sum of the squared residuals for a realization (x, y) of (X, Y)

$$(\beta,\gamma) = \underset{(\beta',\gamma')}{\operatorname{argmin}} \sum_i (y_i - f_{(\beta',\gamma')}(x_i))^2$$

In the case of quantile regression[19,20], $E[Y|X]$ is replaced by a quantile of the response variable Y conditional on X, $Q_\tau[Y|X]$. For each quantile $\tau \in [0,1]$, the linear quantile regression can be written as

$$Q_\tau[Y|X] = f_{(\beta_\tau,\gamma_\tau)}(X)$$

and for a realization (x, y) the slope β_τ and intercept γ_τ parameters are obtained by minimizing the sum of the asymmetrically weighted absolute residuals

$$(\beta_\tau,\gamma_\tau) = \underset{(\beta_\tau',\gamma_\tau')}{\operatorname{argmin}} \sum_i \rho_\tau(y_i - f_{(\beta_\tau',\gamma_\tau')}(x_i))$$

ρ_τ denotes the tilted absolute value function, which gives differing weights to positive and negative residuals r_i depending on the quantile under consideration[20], that is,

$$\rho_\tau(r_i) = \begin{cases} \tau r_i & \text{if } r_i \geq 0 \\ (\tau - 1) r_i & \text{if } r_i < 0 \end{cases}$$

Unlike classical ordinary least-squares regression, quantile regression is not based on parametric assumptions regarding specificities of the underlying data distribution and is flexible for modelling data with heterogeneous conditional distributions (for example, non-constant variance of the data). Here, we assume a linear model for the conditional quantiles.

CECILIA indices. To explore the relation of temperature extremes with soil-moisture deficit, we use here two temperature indices from the CECILIA climate and extreme database (see http://cecilia.dmi.dk/), %HD and HWD_{max} (both computed on a monthly basis). The percentage of hot days (%HD) is defined as the percentage of days with daily maximum temperature $T_{max} >$ 90th reference-period (1961–1990) percentile, and the maximum heat-wave duration (HWD_{max}) is defined as the 90th-percentile-based maximum heat-wave duration (that is, the maximum number of consecutive days with $T_{max} >$ 90th reference-period percentile). The database entails indices computed from observations (high-density station observations from Fig. 1 and E-Obs (ref. 12); indices available for the 1961–2000 period) and from model data of the EU-projects PRUDENCE, ENSEMBLES (transient and ERA-40-driven runs) and CECILIA. As the focus of the present investigation is on observed patterns, only the ENSEMBLES reanalysis (ERA-40) driven simulations are included in the analysis. However, similar results are found for the other sets of regional climate simulations (not shown). Note that E-Obs and the high-density local observations are not fully independent, but the latter include a larger number of stations (∼80 versus 275 stations in the four countries analysed) and are thus better able to represent local effects.

SPI. The SPI (refs 13,24) is applied here as a measure of soil-moisture deficit (negative values indicate drought, positive values indicate wet conditions). The SPI is a widely used drought index and quantifies the precipitation deficit in relation to the long-term probability distribution at a location (that is, the two-parameter Gamma distribution is used here). It can be derived for various timescales. In this analysis the six previous months are considered, which addresses meteorological drought and, indirectly, also agricultural drought to a large extent. The SPI is calculated for each station or grid point individually (depending on the data source), and then domain-averaged for the analyses. Values of −0.5 to −1 correspond to mild droughts, −1 to −1.5 to moderate droughts, −1.5 to −2 to severe droughts and below −2 to extreme droughts. Similarly, values from 0 to 2 correspond to mildly wet to severely wet conditions, and values above 2 to extremely wet conditions.

Spatial aggregation of the station data. The analyses of the article are based on averages of the station data within the respective domains. The results are found to be robust both on the station basis and with other aggregation approaches (see Supplementary Methods).

Soil-moisture regimes of analysed domains. For soil-moisture deficit to impact the surface-energy balance, and hence air temperature, in a given region, evapotranspiration needs to be soil moisture limited[7,27]. This is the case in transitional regions between dry and wet climates[25,27]. An analysis on the basis of flux measurements[29] and observation-driven multimodel estimates[30] has demonstrated the presence of a gradient of soil-moisture regimes (and respective evapotranspiration regimes) on the European continent[26]. Following this analysis, the southeast European domain analysed in this study is characterized by a transitional soil-moisture regime (soil-moisture-limited evapotranspiration regime), whereas the central European domain is characterized by a wet soil-moisture regime (energy-limited evapotranspiration regime).

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Author contributions

M.H. and S.I.S. designed the study and wrote the manuscript. M.H. carried out the analyses. B.O. helped with the statistical analyses. F.B., M.H., P.S., O.B.C. and S.I.S. developed the CECILIA climate and extreme database and the software code for the index calculation. V.A., C.B., H.F. and P.S. provided the observational indices. F.B. helped with the computation of the indices for the ENSEMBLES models.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://npg.nature.com/reprintsandpermissions. Correspondence and requests for materials should be addressed to M.H. or S.I.S.