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- More (less) frequent summer daily warm (cold) record-breaking temperatures in Europe by 2100
- Emergence of human influence projected in the 2030s (2020s) for the warm (cold) records, ± 20 years

Supporting Information:
- Supporting Information S1

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Emergence of human influence on summer record-breaking temperatures over Europe

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Abstract Observational analysis of Europe summer record-breaking temperatures suggests that their occurrence differs from that expected in a stationary climate since the late 1980s. The observed cold and warm record evolution is well simulated by the ensemble mean of 27 coupled models from the Coupled Model Intercomparison Project phase 5 (CMIP5). We find that this evolution is still today within the range of internal variability derived from CMIP5 preindustrial simulations. We then estimate a time of emergence of the summer record anthropogenic influence in a world under a business as usual greenhouse gas emission scenario. We suggest a time of emergence around 2020 for the cold records and 2030 for the warm ones with an uncertainty of ± 20 years. By 2100, the multimodel ensemble mean indicates a tenfold increase of the number of warm records compared to the first half of the twentieth century and the quasi-disappearance of cold records.

1. Introduction

Extreme temperature events have a long history in the global assessment of climate change impacts because of their potential high consequences. The exceptional heat wave that hit Europe in the summer of 2003 had very severe social and environmental effects such as excessive mortality rates throughout Europe as well as forests destruction by fires and significant alpine glaciers volume losses [*Garcia-Herrera et al.*, 2010]. The extreme character of the 2003 heat wave is in part related to the breaking of many temperature records across Europe [*Barriopedro et al.*, 2011]. *Stott et al.* [2004] showed that the human influence has more than doubled the risk of such a severe heat wave, which has now, 10 years later, increased even more [*Christidis et al.*, 2014]. Based on the long Central England Temperature (CET) time series, *King et al.* [2015a] have shown that anthropogenic forcings have induced a thirteenfold increase in the probabilities of occurrence of a warm record year such as 2014.

Europe has recently experienced numerous record-breaking temperatures that take place among a global and sustained change in temperature record statistics. Since the 1980s, the occurrence of daily and monthly warm temperature records is increasing worldwide, while the occurrence of cold ones is decreasing. These changes in record-breaking maximum and minimum surface temperatures (T_{max} and T_{min}, respectively) are observed over the United States [*Meehl et al.*, 2009; *Rowe and Derry*, 2012], Europe [*Wergen et al.*, 2013; *Kendon*, 2014; *Beniston*, 2015; *Bador et al.*, 2015], Australia [*Trewin and Vermont*, 2010; *Lewis and King*, 2015], and also at the global scale [*Coumou et al.*, 2013]. There is a growing body of evidence showing that these changes are inconsistent with those expected in a stationary climate [*Wergen and Krug*, 2010; *Newman et al.*, 2010; *Coumou et al.*, 2013; *Elguindi et al.*, 2012]. These trends in record-breaking daily temperatures are expected to continue in the 21st century simply due to the projected mean warming even without any variability change [*Wergen and Krug*, 2010]. Only a few studies have looked at the time evolution of 21st century record-breaking seasonal temperatures at regional scales. In particular, only a couple of studies have documented the possible future changes in seasonal temperature records over Europe. *Elguindi et al.* [2012] use a set of regional climate models under the A1B SRES scenario to show that the ratio of annual number of T_{max} to T_{min} records steadily rise throughout the 21st century reaching very high values in 2100. They also show that the projected record rate is larger than the predicted one given by a simple nonstationary climate model (linear trend and no change in variance) [*Wergen and Krug*, 2010]. *Bador et al.* [2015] suggest that the appropriate detection of an anthropogenic influence on temperature records must fully account for internal variability of the climate system. Indeed, low-frequency variations due to internal variability, for instance due to variability of the Atlantic meridional overturning circulation, may possibly lead for a few decades, to a different record behavior from that expected in a stationary climate. Using an estimate of internal variability based on one climate model, they show that the emergence of a significant change in temperature records only happens in the 2030s in this particular model. Both studies also document spatial and seasonal contrasts pointing out the largest increase in summer T_{max} records over the Mediterranean region and the lowest number of winter T_{min} records over Scandinavia and northern-eastern European regions.

Here we investigate the past (1900–2005) and future (2006–2100) changes in T_{max} and T_{min} records in summer over Europe from a large ensemble of CMIP5 models and the E-OBS observations. For the past, we use historical simulations driven by observed natural and anthropogenic forcings. For the future, we focus on simulations driven by the business as usual greenhouse gas emission scenario Radiative Concentration Pathway 8.5 (RCP8.5). We also define and estimate a time of emergence (ToE) of the anthropogenic influence on summer record-breaking temperatures. We finally assess and discuss the detectability of an anthropogenic influence on the time evolution of summer T_{max} and T_{min} records.

2. Data and Methods

2.1. Observed and Simulated Temperatures

We focus on daily T_{min} and T_{max} temperatures over continental Europe (10°W–28°E; 37–60°N). The observations span the 1950–2013 period and are taken from the E-OBS data set, on a regular grid with $0.5° \times 0.5°$ horizontal resolution (version 9.0) [*Haylock et al.*, 2008]. Modeled temperatures are taken from simulations performed with a large ensemble (LE) of 27 CMIP5 climate models (see Table S1 in the supporting information). We include all model grid points having a land fraction of 90% or more. We use the multimodel ensemble (MME) mean as our best estimate of the response to external forcing (the forced response).

We first use a set of historical simulations (HIST) covering the 1900–2005 period and driven by observed external forcings (solar and volcanic activity, natural and anthropogenic aerosols and greenhouse gases). For the future (2006–2100), we use simulations in which anthropogenic forcings follow the scenario RCP8.5 [*van Vuuren et al.*, 2007]. We also analyze the CMIP5 control simulations (CTRL), with constant external forcings at their preindustrial 1850 values. We also select a reduced ensemble (RE) of five models having at least 500 years of control simulation and a minimum of three members for the historical and future simulations (see Table S1).

2.2. Record-Breaking Temperatures

A warm (cold) record is broken at the *n*th year after the initialization when T_{max} (T_{min}) is higher (lower) than the values of all previous years, in agreement with previous studies [e.g. *Arnold et al.*, 1998; *Meehl et al.*, 2009; *Wergen and Krug*, 2010].

The record calculation is performed for each calendar day of the summer defined as the June, July, and August (JJA) months. For a given year, the total number of records is simply the sum of records over all (92) JJA days and all grid points of continental Europe. As temperature records are both spatially and temporally correlated, they will therefore have a tendency to cluster in both space and time. We assume that the model CTRL spatiotemporal covariance structure can be used to assess the statistical significance of record changes (see Text S1).

The record evolutions are represented under the normalized form where the expected number of records for all years is 1 for a stationary climate (see Text S1). In a stationary climate, the record numbers are theoretically expected to decrease with time. The normalized form masks this decrease and thus allows a better visualization of the record evolution. Note that the record changes are always defined relative to a given starting date (see Figure S1 about the differences in record evolution with different starting dates). This is analogous in some sense to the sensitivity of the magnitude of expected future changes with respect to the reference period.

As we are interested in the emergence of an anthropogenic influence, our null hypothesis $H0$ is as follows: *changes in record occurrence are only driven by internal variability*. We then estimate the range (90% confidence interval) of changes purely due to internal variability based on a block bootstrap approach using the CTRL simulations of the RE models (see Text S2 and Figure S2).

2.3. Time of Emergence (ToE)

Emergence can be claimed from year n if the record evolution is continuously outside the internal variability 90% confidence interval for all $m > n$ (meaning that we can strongly reject $H0$ at the 10% level). However, this

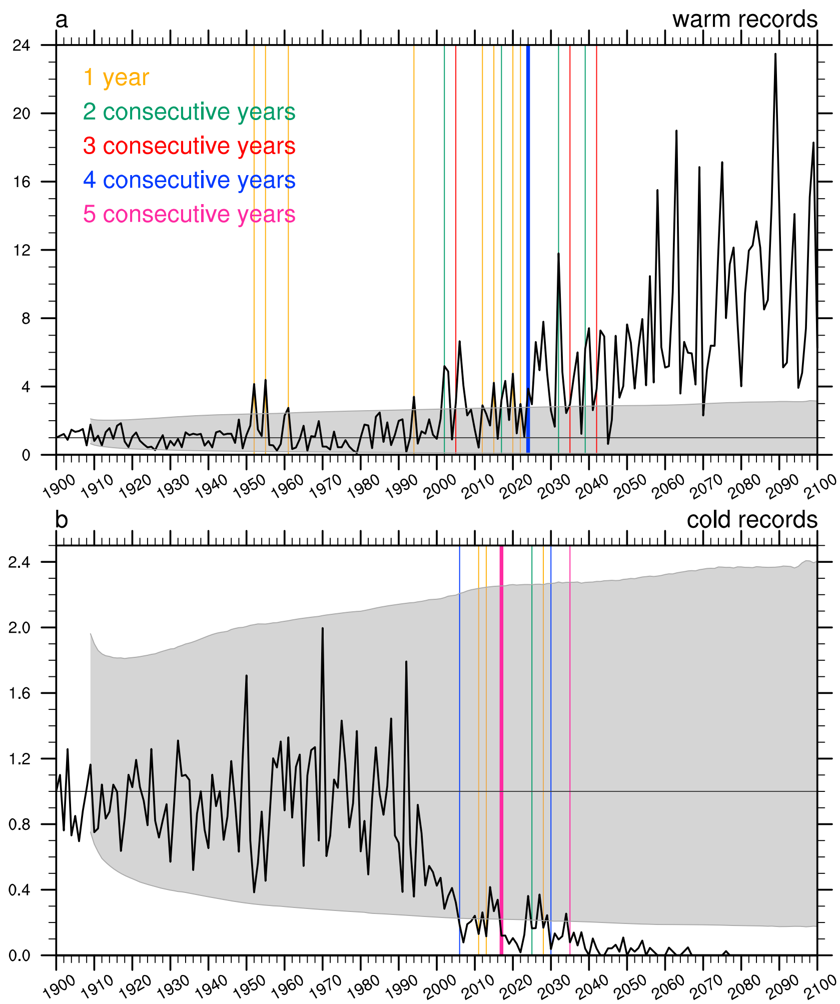

Figure 1. HIST and RCP8.5 evolutions of the annual number of summer (a) warm and (b) cold records in Europe from a random member (black line) of the CanESM2 model. Shaded grey areas correspond to the 90% confidence interval of the record evolutions driven by internal variability only. Vertical thin colored lines refer to the first year of an exceeding event (see the color-duration relation in Figure 1a). The vertical thick line refers to the detected ToE.

is a very conservative test as just 1 year with a record number occurrence within the 90% confidence interval can then delay the emergence. In addition, the RCP8.5 simulations do not go beyond 2100 formally preventing a definitive emergence. Following *Christiansen* [2013], we propose a different approach based on the occurrence of an unprecedented exceeding event. We define an exceeding event as being a series of $m = 1, 2, 3, \ldots$ consecutive years where the record evolution is always outside the 90% confidence interval. The ToE is finally defined as the first year of an unprecedented exceeding event, meaning one of a duration that never occurred in our internal variability sample (4 and 5 years for warm and cold records, respectively; see Text S3 and Figure S3). The final step verifies that more than 50% of the remaining years (between the ToE and 2100) are outside the 90% confidence interval (the choice of 50% is indeed a conservative one; see Figures S4 and S5). If no ToE is found before 2081, then we do not attribute any ToE for that record time series to account for the possible influence of an arbitrary ending date on the results [*Diffenbaugh and Scherer*, 2011; *Hawkins et al.*, 2014]. Finally, the ToEs are evaluated from raw records to minimize the starting date dependence associated with the normalized form. Figure 1 illustrates the emergence of the anthropogenic influence on a simulated evolution of cold and warm records. Several exceeding events happen before and after the detected ToE, as explained above.

Our ToE definition is in broad agreement with previous studies based on signal to noise thresholds between 1 and 2 as well as on a measure of persistence [*Mahlstein et al.*, 2011; *Hawkins and Sutton*, 2012; *Lyu et al.*, 2014].

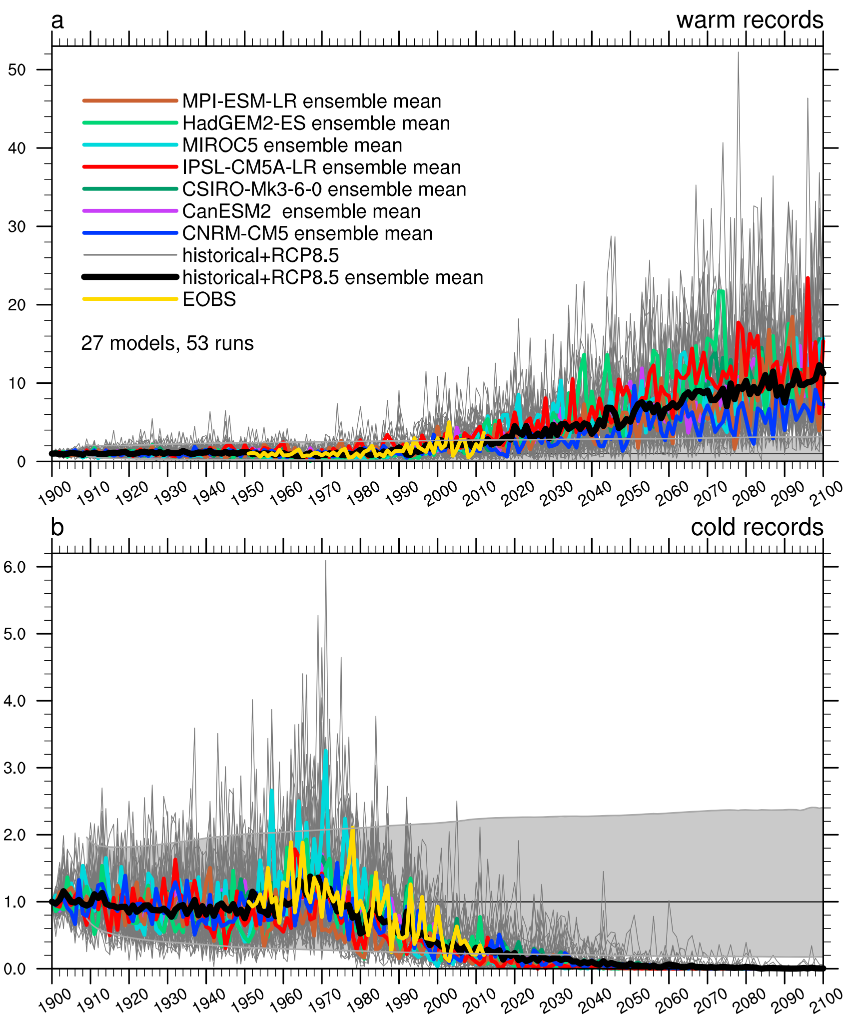

Figure 2. Observed (yellow; E-OBS dataset), HIST and RCP8.5 evolutions of the annual number of summer daily (a) warm and (b) cold records in Europe. Grey lines refer to the 53 simulations of the LE models and color lines to the model ensemble means, with the LE MME mean in black. Shaded grey areas correspond to the 90% confidence interval of the record evolutions driven by internal variability only.

3. Past and Future Changes in Daily Cold and Warm Record-Breaking Temperatures

During the first decades of the twentieth century, both the observed and simulated record evolutions remain close to one, the expected normalized number of records in a stationary climate (Figures 2a and 2b). Some decadal variations are seen in the 1960s and 1970s, with a higher number of cold records as noted by *Christiansen* [2013]. The summer record evolution in Europe differs from the one expected in a stationary climate from the late 1980s onwards. Both the observations and the models show a strong decrease and increase in the number of summer cold and warm records, respectively.

Averaged over the last three decades of the 21st century, the LE MME mean yields a tenfold (9.5 ± 3.3, with the 90% confidence interval given by 1.64 times the intermodel standard deviation) increase in the average number of summer warm records in Europe compared to the early twentieth century. Ensemble mean values range from 6 to 12 among the models with several members suggesting that model uncertainty is a significant fraction of the total uncertainty. Using only the (7) models having at least three members, one can partition the total uncertainty between model uncertainty and internal variability. As expected, the variance associated to model uncertainty represents 93% of the total variance while the internal variability contribution is only 7%. Looking at individual simulations, the number of summer records ranges from 0 to 50, showing the large amplitude of interannual variability.

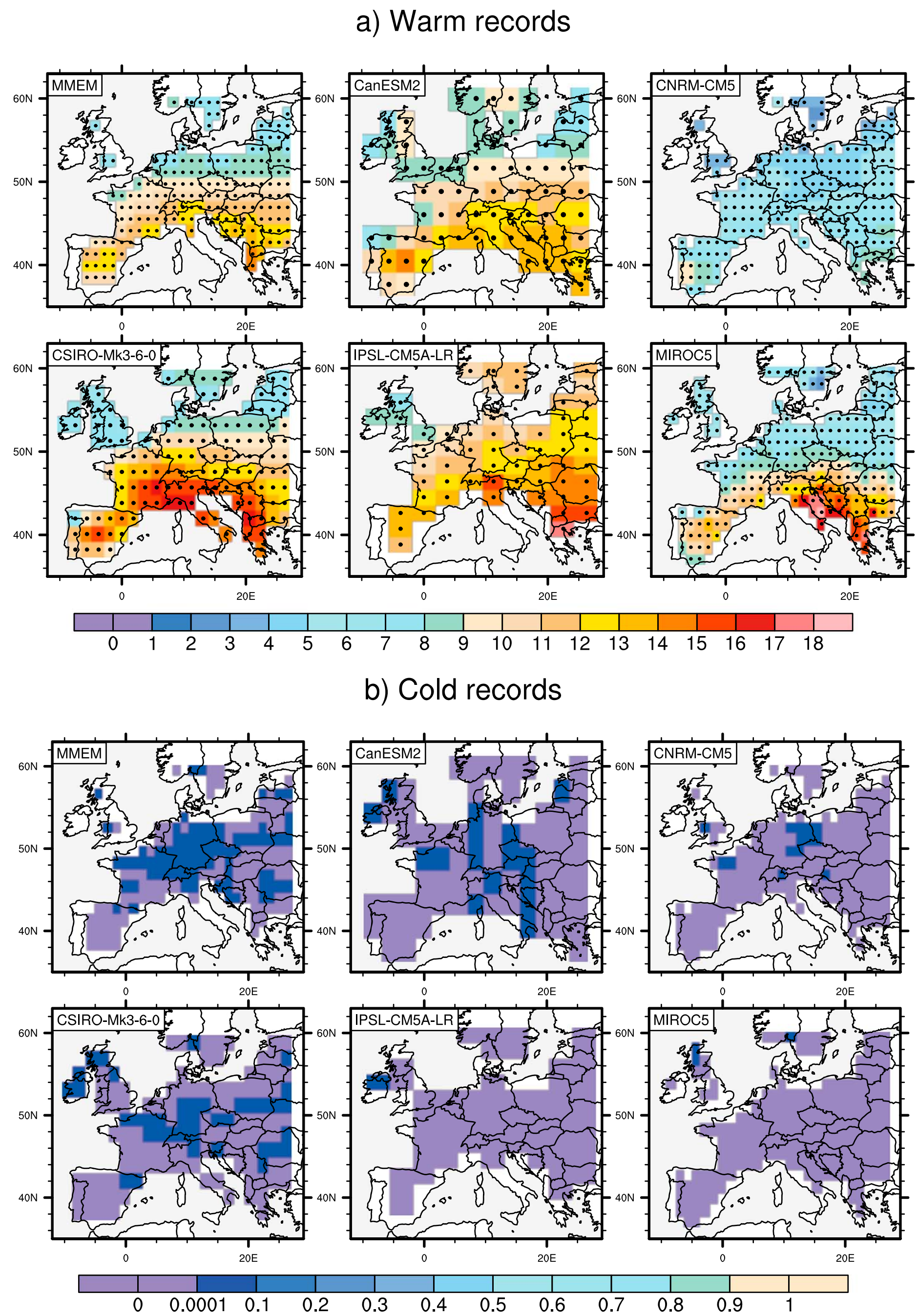

Figure 3. Spatial distribution of the 2071–2100 averaged number of summer daily (a) warm and (b) cold records in the RCP8.5 ensemble mean of the RE models. Dots indicate a mean number of warm records higher than the upper limit of the 90% confidence interval of the record evolutions driven by internal variability (cold records cannot be tested). Each model is compared to its respective confidence interval, whereas the MME mean is compared to the multimodel estimate of the confidence interval. All model temperatures were interpolated on the CNRM-CM5 grid for the multimodel estimate.

In stark contrast, all the cold record evolutions of the 53 simulations tend to zero. The spread is much lower than for the warm records, which is partly explained by a decrease in interannual variability as the number of records approaches zero. Over the last three decades of the 21st century, no cold record is broken over Europe in summer for the majority of models and simulations.

The comparison of the LE MME mean to the range purely driven by internal variability can be used to qualitatively assess the emergence of the forced signal on the records. The MME mean of the record evolution seems to emerge from the internal variability 90% confidence interval starting from the 2020s for both cold and warm records. A larger intermodel spread is noted for the warm records. For example, the warm record evolution is still within the internal variability range in the early 2050s for CNRM-CM5 while it emerges in the 2010s for IPSL-CM5A-LR (see also Figure S2). These estimations are completed by the assessment of the ToE for each individual simulation and model in the next section.

The largest increases in summer warm records are generally found on the Mediterranean edge (Figure 3a), consistently with *Elguindi et al*. [2012]. A strong meridional gradient is noted in the RE MME mean. A large intermodel spread is also noted, with the greatest increase in warm records projected by the CSIRO-MK3-6-0 and MIROC5 models and the lowest increase projected by the CNRM-CM5 model. The projected mean number of summer warm records shows a fourteenfold (fivefold) increase in southern (northern) Europe by the end of the 21st century. Using a more recent starting date (1951 instead of 1900) leads to a tenfold (fourfold) increase (see section 2.2).

At the grid point scale, the RE MME mean estimate is outside the variability range expected from internal variability alone regarding the evolution of warm records everywhere in Europe. It is also true for all individual models, except for CNRM-CM5 regarding a few grid points in northern Europe (Figure 3a).

Almost no cold summer records are broken in the last decades of the 21st century everywhere in Europe (Figure 3b) with a very good agreement among models. All models project a minimum tenfold decrease in the mean number of cold records over all Europe. Note that even in a stationary climate, after 200 years, the probability for a record to be broken is very small, especially at a particular grid point. The lower limit of the confidence interval is therefore bounded by 0 for many grid points precluding its use for a complete statistical assessment.

4. Time of Emergence and Sources of Spread

As expected from Figure 2, the emergence of the anthropogenic influence on the number of daily records from the noise due to internal variability seems to occur somewhat earlier for the cold records than the warm records. Over the United States, *Scherer and Diffenbaugh* [2013] show contrasting results, with earlier emergence for frequency of warm than cold temperature extremes. A multiseasonal analysis on the same variable (extreme or record) and region is needed to assess the agreement or lack of with their work.

The LE MME mean estimate of the ToE for warm (cold) records is around 2030 (2020) with an intermodel standard deviation of 19 (21) years (see Tables S2 and S3). The spread is due to both model uncertainty and internal variability. The importance of model uncertainty is estimated again using the (7) models having at least three members. The intermodel standard deviations obtained are roughly 10 years and 7 years for warm and cold records, respectively, which corresponds, respectively, to about one half and one third of the total uncertainty. It highlights the significant impact of internal variability on the estimation of the ToE uncertainty range. Note that no emergence is detected for the observations. *King et al*. [2015b] recently showed similar results for the CET time series, with no ToE of summer temperature extremes up to now.

Previous work has shown that for a conceptual model in which climate change simply consists in a linear warming trend with no change in variability, the increase in warm records is proportional to the signal to noise ratio (SNR) defined as the mean temperature change to the present-day variability given by the standard deviation of the daily temperature distribution [*Wergen and Krug*, 2010; *Newman et al*., 2010; *Rahmstorf and Coumou*, 2011]. This simple theoretical framework is used here as a basis for understanding the intermodel spread in the simulated change in the number of records in the middle of the 21st century (2021–2050). While this analysis could have been performed on a later period (2071–2100) for the warm records, the disappearance of cold records from the 2050s makes its application useless for the latter as the spread is zero.

A significant relationship is found between the mean increase (decrease) in the number of warm (cold) records and the changes in T_{max} (T_{min}) (Figures 4a and 4d). A relationship is also found between the mean changes in the number of cold records and the present-day variability of T_{min} (Figure 4e). However, no significant similar relationship exists for warm records and T_{max} (Figure 4b). Note that the CMIP5 models do not seem to overestimate or underestimate observed T_{min} and T_{max} variability (Figures 4b and 4e). Finally, the best metric explaining the intermodel spread in the changes in warm and cold records is the

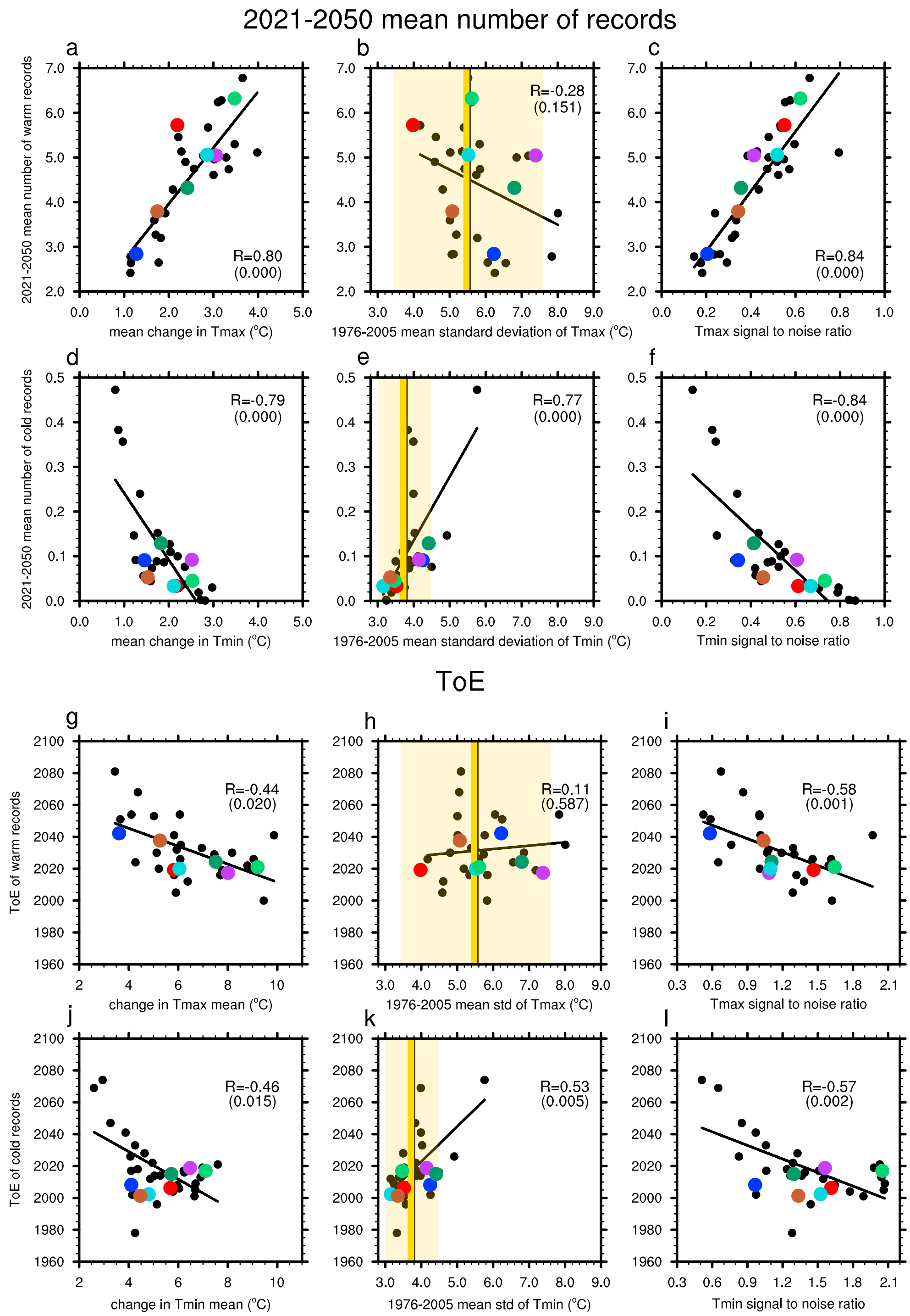

Figure 4. Scatter plots of the mean number of summer (a–c) warm and (d–f) cold records in Europe against (Figures 4a and 4d) the 1976–2005 to 2021–2050 mean changes in summer T_{max} and T_{min}, (Figures 4b and 4e) the 1976–2005 mean standard deviation of summer T_{max} and T_{min}, (Figures 4e and 4f) the ratio of these two components. Same as Figures 4a–4f for the (g–i) warm and (j–l) cold records ToE, with the mean changes in summer T_{max} and T_{min} estimated between the periods 1976–2005 and 2071–2100. Only one simulation per LE models is considered (black dots). Colored dots refer to the models ensemble mean (see Figure 2 for the color-model relation). The regression line, value of the Spearman's rank correlation (R) and associated p value (in brackets) are indicated on each panel. Vertical gold and black lines refer, respectively, to the 1976–2005 observed and multimodel median values of T_{max} and T_{min} standard deviations. Gold shading refers to the 90% confidence interval of 30 year period standard deviation given by the CTRL multimodel estimate of internal variability.

SNR (Figures 4c and 4f). The future mean warming mostly controls the intermodel spread in the changes of the number of warm and cold records while present-day variability has a significant contribution only for cold records. Note also that there are significant changes in terms of model standard deviation of T_{max} and T_{min} between 2021–2050 and 1976–2005 (an increase of 0.4 ± 0.24 and 0.23 ± 0.13 °C, respectively) and that these values more than double at the end of the century.

Figure 4 also shows the same analysis for the ToE rather than the changes in the number of records. The results are very similar, although the relationships are generally slightly weaker for the warm record ToE than for the changes in the number of warm records. In particular, as could be expected, the evolution of records tends to emerge earlier from the noise in the models characterized by a stronger warming. The earlier cold record ToE is likely to be related to a stronger T_{min} SNR due to a lower present-day variability. As there is a significant model relationship between cold record ToE and present-day T_{min} variability, the knowledge of the observed T_{min} standard deviation can be used to yield a qualitative mean estimate of the predicted "observed" cold record ToE between 2015 and 2020.

5. Summary and Discussion

We have used an observed data set and an ensemble of 27 climate models to assess past and future changes in European daily cold and warm summer record-breaking temperatures. Since the 1980s, the observed and simulated record evolutions differ from that of the stationary climate that correctly represented the first decades of the observed period (1950–1980). However, they are both within the range of possible changes due to internal variability by the beginning of the 21st century.

By the end of the 21st century, the MME mean shows a projected number of summer daily warm records roughly 10 times higher than in the first decades of the observed period. All the models project an increase in summer warm records with a North-South gradient and the largest changes over the Mediterranean region. There is a significant dispersion in the magnitude of the changes mostly due to model uncertainty.

Concerning the daily cold record-breaking temperatures, the CMIP5 models agree on a large decrease for the future European summers. Over the last three decades of the century, breaking a new daily cold record is projected to be extremely difficult anywhere in Europe.

From the ensemble of CMIP5 models, the ToE of a cold and warm record evolution inconsistent with internal variability is estimated to happen around 2020 and 2030, with an uncertainty range of ± 20 years. Our results thus suggest that the model estimate ToE of both cold and warm records happen quite early in the 21st century in Europe. As the mean temperature change ToE happens earlier in the Tropics [*Mahlstein et al.*, 2011; *Diffenbaugh and Scherer*, 2011; *Hawkins and Sutton*, 2012], some tropical regions could already be experiencing record changes inconsistent with internal variability, as suggested for temperature extremes by *King et al*. [2015b].

As predicted by a simple theoretical model based on a linear warming trend and no change in variability, our results show that there is a significant relationship between the projected mean cold and warm record changes and ToE, on one hand, and the mean temperature change. They also indicate an earlier cold record ToE and stronger cold record decrease for models having smaller present-day variability. The signal to noise ratio defined by the mean temperature change over present-day temperature variability is higher for T_{min} than for T_{max} due to a larger present-day T_{max} variability. This partly explains a stronger decrease in Europe summer cold records than an increase in warm records as well as an earlier ToE for the cold records. Hence, the higher variability of T_{max} tends to delay the warm record ToE despite a T_{max} mean warming similar or even larger than for T_{min}. An additional factor contributing to the later T_{max} ToE could be the larger increase in variability for T_{max} compared to T_{min} during the 21st century. This simulated variability change, in contrast with the assumption of the simple model, could also explain why the CMIP5 model spread is not fully explained by the difference in signal to noise ratio.

Finally, an analysis of the dynamical and thermodynamical mechanisms responsible for the breaking of cold and warm temperature records could lead to a better understanding and constraint of the model dispersion. This would improve the projection of record-breaking temperatures that could be experienced in future European summers.

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