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RESEARCH

Long-term trend and variability in surface temperatures over Emilia-Romagna from 1962 to 2022

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Abstract
Scientific interest is increasingly drawn towards regional meteorological extremes, given their impacts on populations, infrastructure, and ecosystems. These extremes are shaped by complex interactions between internal climate variability and long-term trends. The aim of the present work is to evaluate changes in high-frequency variability and the influence of long-term trends on the frequency of occurrences of extremes, with a focus on surface temperatures over the period from 1962 to 2022 in Emilia-Romagna, a region of Northern Italy. Daily data of 2 m air temperatures averaged over the region are retrieved from ERACLITO, a high-resolution climate analysis. The distributions of daily temperature anomalies show a general broadening in 1992–2022 with respect to 1962–1991. This is true for maximum, minimum, and mean daily surface temperatures, especially during the summer and spring seasons. A significant warming trend of 0.37 °C/decade is detected in annual mean surface temperatures over the period considered. The study is completed with a comparison between the observed frequency of record-breaking annual temperature events, a hypothetical stationary climate distribution and a theoretical derivation that accounts for changes in trends and variability. During the last decade, the theoretical count of extreme events is 1.26, which yields a likelihood of 86% that this is owed to the trend rather than interannual variability. Idealized experiments demonstrate that the expected occurrences of record-breaking events in future decades depend on the warming rate rather than the warming level. Finally, an analysis performed at seasonal level shows that the majority (minority) of record events are occurring in the summer (spring) seasons.

1 Introduction

The most relevant and widely acknowledged consequence of the anthropogenic increase in greenhouse gas concentrations is the rise in global surface temperatures. The presence of global warming is anticipated to lead to an enhanced frequency of extreme events (Christidis et al. 2014; Molina et al. 2020; Seneviratne et al. 2021) with extensive impacts on human activities and health (e.g., Fouillet et al. 2006; Turco et al. 2018). The Euro-Mediterranean region has been identified as one of the *hot spots* of climate change (Giorgi 2006), where the risk of enhanced frequency of extreme events is rising more rapidly with respect to the global scale (Scoccimarro et al. 2016; Lionello and Scarascia 2018; Seneviratne et al. 2021). A significant decline in mean precipitation for specific seasons has been observed, coinciding with an increased frequency of heat waves, extreme precipitation events, and droughts (Russo et al. 2015; Spinoni et al. 2015; Cramer et al. 2018; Pavan et al. 2019; Vogel et al. 2021). A general tendency of annual-mean conditions in the Mediterranean to become warmer and drier is suggested by many coupled model results under scenario conditions (Vicente-Serrano et al. 2014; Spinoni et al. 2017; Raymond et al. 2019; Seneviratne et al. 2021; Baronetti et al. 2022).

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Although extreme hydro-meteorological hazards and global warming-induced trends in temperature and precipitation extremes have been analyzed in recent years, there has been limited focus on their spatio-temporal variability in the Italian peninsula, especially within the Po Valley (Brunetti et al. 2001; Tomozeiu et al. 2006; Pavan et al. 2008, 2019; Tomei et al. 2010; Petkov 2015; Antolini et al. 2017; Baronetti et al. 2020). For instance, Tomozeiu et al. (2006) showed a significant seasonal increase in both mean maximum and minimum temperatures particularly during summer and winter. Pavan et al. (2008) described the observed long-term variability of precipitation climate indices including the frequency of intense events and of the length of dry spells in Emilia-Romagna between 1951 and 2004. Pavan et al. (2019) described the observed long-term variability of climate indices obtained from daily precipitation data of the ARCIS climate observational gridded dataset covering North-Central Italy from 1961 to the present.

Unlike previous studies, this focuses on the evaluation of long-term changes in temperature variability and on the role of variability and warming trends in altering the likelihood of occurrence of temperature records in Emilia-Romagna, during the period 1962–2022. The paper is structured as follows: Section 2 includes a brief description of experimental data and methods. In Section 3, the distributions of daily temperature indices are analyzed and a theoretical framework aimed at assessing the mutual role of variability and warming trend is put forth. Conclusions and discussion of results are presented in Section 4.

2 Data and methods

The temperature data are obtained from ERACLITO, a daily high-resolution gridded climatic data set for Emilia-Romagna, Italy, covering the period from 1962 to the present (Antolini et al. 2015). The dataset consists of daily minimum and maximum temperature data obtained by interpolating over a regular grid of about 5 km resolution the observed data collected by ARPAE (*Agenzia Regionale Prevenzione Ambiente Energia*) in Emilia-Romagna, and designed in order to describe climate variability over the region. All observational data used as input for the analysis have been checked for quality, temporal consistency, statistical homogeneity and synchronicity (Antolini et al. 2015). Gridded data are finally averaged across the region, so as to obtain a time series of spatially averaged daily indices over the period 1962–2022.

Changes in the high-frequency variability of daily temperature indices are analyzed using a practical approach centered around variance-related metrics. In this respect, high-frequency variability is defined as the variance observed within daily temperature indices distributions after applying a high band-pass filter. Long-term changes in high-frequency variability are described by comparing the findings for the periods 1962–1991 and 1992–2022.

In the context of annual mean temperatures and under the assumption of a hypothetical stationary climate, the expected number of record events within a period of length n is expected to decrease in time following the expression:

$$\sum_{i=1}^{n} 1/i. \tag{1}$$

However, Rahmstorf and Coumou (2011) found that, in the presence of a warming trend, the number of heat extreme events becomes proportional to the ratio of the linear warming trend and the short-term variability of temperature data. They suggested that assuming that the distribution of annual mean temperatures is approximately Gaussian, the number of theoretical extreme events for a given period can be calculated as a function of a time-dependent mean and a standard deviation owed to short-term interannual variability. In this respect, the analytical solution for the annual occurrence of record-breaking temperature events can be expressed as a combination of two terms: the probability that, at time t, a value x has not been exceeded in the past record and the probability that x occurs at that time. Following this framework, the authors stated that the probability of an unprecedented record event at a specific time step, denoted by t_n, can be decomposed into:

$$P(t_n) = \int_{-\infty}^{+\infty} f(x, t_n) \prod_{i=1}^{n-1} F(x, t_i) \partial x, \tag{2}$$

where $f(x, t_n)$ is the function that determines the probability of recording a value x at time t_n, and $F(x, t_i)$ is the cumulative distribution function that quantifies the probability that a value x has not been surpassed at times prior to t_n. In the context of Gaussian distributed time series, Eq. (2) becomes:

$$P(t_n) = \int_{-\infty}^{+\infty} \left[\frac{1}{\sqrt{2\pi\sigma_{t_n}^2}} e^{-\frac{(x-\mu_{t_n})2}{2\sigma_{t_n}^2}} \right] \prod_{i=1}^{n-1} \left(\frac{1}{2} + \frac{1}{2} erf\left(\frac{x - \mu_{t_i}}{\sigma_{t_i}\sqrt{2}} \right) \right) \partial x, \tag{3}$$

where μ_{t_n} is the time-dependent average of the distribution, σ_{t_n} is the time-dependent standard deviation owed to interannual variability, and *erf* stands for ordinary error function. The average of the distribution might be considered as linearly varying in time, as in Rahmstorf and Coumou (2011), or nonlinear (e.g. Fischer et al. 2021).

Furthermore, the relationship between the expected number of record events, the short-term variability, and long-term trends is assessed through ad hoc idealized experiments, in which different possible future long term variabilities are assumed to occur. Five scenarios are considered for the period 2023–2082: constant linear trend and interannual variability (*Trend*×*1*, *Var*×*1*), transient doubling of the linear trend and constant interannual variability (*Trend*×*2 transient*, *Var*×*1*), abrupt doubling of the linear trend and constant interannual variability (*Trend*×*2 abrupt*, *Var*×*1*), constant linear trend and transient doubling of interannual variability (*Trend*×*1*, *Var* ×*2*), and constant linear trend and transient 50% reduction of interannual variability (*Trend*×*1*, *Var:2*). The term "transient" refers to a linear increase (or reduction) in quantity until it reaches the desired value at the end of the scenario's period. These idealized scenarios could be viewed as a framework for understanding how future changes in long-term trends and variability might interact to influence the likelihood of occurrence of record annual temperatures.

Then, the theoretical probability of observing an extreme event in a given decade is compared to that of a stationary climate, namely a climate with no linear long-term trend. In this regard, the annual normalized difference between the probabilities of records calculated using Eq. (3) and Eq. (1) quantifies the likelihood that, at a given time, the records are attributed to the warming trend rather than to variability. This is done to filter out the role of interannual variability in the modulation of the number of extreme temperature events.

3 Results

3.1 Distribution of daily temperatures

This section aims to assess the changes in the distribution of daily temperatures over the period considered. First, daily anomalies are calculated by subtracting from the daily value a 7-day centered moving window average, allowing to isolate the high frequency component of the variance of daily temperature variability. Comparable results are achieved when using temporal widths ranging from 4 to 15 days (not shown). Figure 1a shows the temperature anomalies frequency distribution for period *I* (1962–1991, blue) and period *II* (1992–2022, orange), while Fig. 1b plots the empirical probability density function, calculated by implementing a kernel density estimate for the same data. The percentages at the top of each vertical bar indicate the normalized difference between period *II* and period *I* frequencies. The plot shows a decrease in the number of days with values around the mean, compensated by a growth in the frequency of the extremes. The variance has increased in the recent period by about 12% of its former value, leading to a broadening of the frequency density function on both sides of the distribution's tail. A seasonal analysis of the same data suggests that the largest temperature departures from the respective mean are more frequent in summer, with a larger occurrence of positive anomalies, as shown in Figs. 1c and 1d.

During spring most of the intense temperature anomalies are negative, suggesting that, although the spring mean value of daily temperature has increased in 1992–2022 as in all other seasons, the number of anomalous cold days with respect to the new warmer climate has increased (not shown). Winter does not exhibit substantial changes between period *I* and period *II* frequency density functions, while in autumn, both negative and positive extreme frequencies are enhanced in the latter period (not shown). These results indicate that daily mean temperatures are becoming more variable at short timescales, with an increase in the frequency

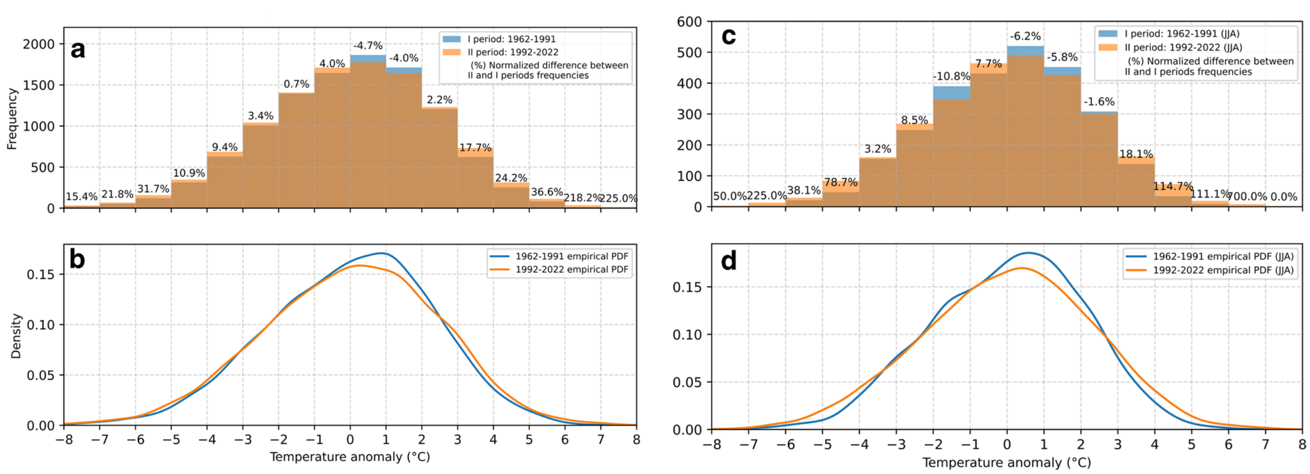

Fig. 1 (**a**) Frequency histogram distribution of daily temperature anomalies for period *I* (1962–1991, blue bars) and period *II* (1992–2022, orange bars). The percentages at the top of each bar indicate the normalized difference between periods *II* and *I* frequencies. (**b**) Empirical Probability Density Functions (PDFs) for daily temperature anomalies within period *I* (1962–1991, blue curve) and period *II* (1992–2022, orange curve). (**c**, **d**) As in (a, b) but for the summer season (JJA)

of cold and warm extreme days, depending on the season considered.

In order to quantify the change in daily temperature variability, in Table 1 are listed for each season and parameter, the changes in variances between the two periods considered, normalized with respect to the former one. For each parameter, values are reported for the total variance, computed with respect to the whole period average, and for the high-frequency variance.the end of the last year, the total number of expected events

In general, there has been a notable increase in the total variance of daily maximum temperatures during summer, winter, and spring. Conversely, a decrease in total variance is noticeable in winter, autumn, and summer for minimum temperatures. Moreover, the high-frequency variability of daily temperature (anomalies) within summer, spring and autumn has increased considerably in the period 1992–2022, while it has decreased slightly during the winter season. Interestingly, the increase in mean temperature anomaly variances in autumn corresponds to a decrease in mean temperature total variability. This suggests that, during this season, even if mean temperatures have become overall less variable, the occurrences of extreme events at high-frequency timescales have increased considerably.

3.2 Record-breaking annual temperatures

Several studies have analyzed the frequency of occurrence of events consisting of unprecedented temperature extremes, assuming a stationary climate, defined as meteorological conditions without significant linear trends in long-term values (Krug 2007; Meehl et al. 2009; King 2017). In such conditions, applying Eq. (1) to the data-set of mean annual temperatures for Emilia-Romagna over the period from 1962 to 2022, by the end of the last year, the total number of expected events should be about 4.7, with most of the extremes in the first decade of the period. Within the first 10 years the expected cumulative number of extreme events should be around 3, and the number of expected extreme events occurring in the last decade should be around 0.18. However, in a warming world the number of record-breaking temperatures is not declining with time following *1/n,* but increasing. In order to evaluate the expected number of record events in the presence of an increasing trend, following the methodology implemented in Rahmstorf and Coumou (2011), described in the Data and Methods section, the time series of annual mean surface temperatures is decomposed into a trend and a noise process. The noise is defined to have the standard deviation of the data in a 25-year moving window, and it is smoothed by implementing a third-order Savitzky-Golay filter (Press and Teukolsky 1990).

By construction, the standard deviation-based noise component is autocorrelated at various lead-time lags. To evaluate the extent to which the interannual variability noise component adheres to a Gaussian distribution, two tests have been conducted: the Anderson–Darling test (Stephens 1974) and the D'Agostino K-squared test (D'Agostino 1971). The Anderson–Darling test is suitable at identifying deviations from a normal distribution, particularly in the distribution's tails. Conversely, the D'Agostino K-squared test relies on transformations of sample kurtosis and skewness, which are indicators of the distribution's shape. The noise process meets the Gaussian criteria, although not at all significance levels, according to the Anderson–Darling significant test. By implementing the D'Agostino K-squared test, the noise data might be considered as Gaussian. It is then assumed that the noise process can be considered Gaussian.

As a sensitivity test for the choice of the noise component, a smoothed non-linear trend is computed by implementing a third-order Savitzky-Golay filter, and a noise process is computed as the difference between the data and the smoothed non-linear trend. In this case, the distribution of the noise is approximately Gaussian (not shown), as confirmed by applying an Anderson–Darling significance test, at various levels of confidence, spanning from 15 to 1%. Furthermore, the residual-based variability data was tested for hidden data autocorrelation by computing the lagged autocorrelation coefficients (not shown) and no significant lagged autocorrelation was found as the lag-1 autocorrelation coefficient was $r_{lag-1} = -0.02$, which largely differs from the 95% confidence level.

Table 1 Normalized seasonal change of high-frequency and total variances of daily surface temperature indices in 1992–2022 with respect to 1962–1991. Tmin, Tmean, and Tmax indicate the minimum, mean, and maximum daily temperatures, respectively. Tanom represents the high-frequency component of daily temperature anomalies, calculated using a sliding-window approach

SEASON	*Tmin total variance change*	*Tmax total variance change*	*Tanom high-frequency variance change*	*Tmean total variance change*
JJA (summer)	-3,5%	6,8%	24,0%	6,0%
DJF (winter)	-10,3%	14,0%	-2,2%	-5,1%
MAM (spring)	10,9%	9,1%	13,8%	10,2%
SON (autumn)	-11,9%	-0,5%	18,9%	-7,1%

It is essential to note that the analytical formula presented in Eq. (3) yields comparable results when implementing both aforementioned noise processes (not shown).

As a result of these tests, the time series can be considered as a nearly Gaussian noise superimposed to a long-term linear trend equal to 0.37 °C/decade. The trend is significant with respect to a Mann–Kendall monotonic test. To assess the robustness of the methodology, a Monte Carlo experiment with 100000 synthetic time series was performed, by combining a white noise component and a long-term linear trend. Figures 2a and 2b show the observed and one of the synthetic time series, respectively, as well as the least-square linear regression fit (gray dashed line). The 36% of record events (red stars) appear in the first decade (4 out 11 records), both in the observed and in the synthetic time series.

Now, the analytical solution given in Eq. (3) is applied by using a long-term linear trend and compared to the results obtained in the Monte Carlo experiments. The theoretical count of record events coincides with the average of records in the Monte Carlo simulations (not shown). Confidence intervals are defined as the 5th and 95th Gaussian percentiles of the Monte Carlo records.

At the same time, similarly to Fischer et al. (2021), it is decided to apply this theoretical framework to several different experimental scenarios over the period from 2023 to 2082. Figure 3 shows for the period 1962–2022 the observed number of extreme temperature events per decade (blue dashed curve), smoothed by applying a third-order Savitzky-Golay filter, those expected over the same period by the theoretical Eq. (3) (black solid curve), together with the confidence intervals of the Monte Carlo experiments (gray area). The observed number of record-breaking events is consistent with the theoretical ones. The theoretical and observed records reach two local maxima during the 90s and the last decade concurrently with a decrease in interannual variability (not shown). In the last decade, the number of breaking events is 1.07 and 1.26 for the observed and theoretical curves, respectively. It is now compared the number of expected extremes in the last decade, as estimated with the formula (3), with the number of extremes expected in a stationary climate (green curve) which is 0.18. The normalized difference between the two values yields a probability of about 86% that the record events are modulated by the observed trend rather than the interannual variability. In a nonlinear trend configuration this probability reaches 87%. The same exercise was also implemented for extreme events surpassing a fixed threshold. In this case, the frequency of extreme events per decade increases more rapidly compared to the record-breaking framework (not shown). For instance, in the case of setting the threshold at 2 standard deviations above the mean, the theoretical and observed records during the last decade amount to 4.83 and 4.45, respectively.

Figure 3 also shows for the period 2023–2082 the number of record breaking events for each idealized forcing experiment in terms of a 10-year centered moving window. The experiments show that the theoretical probability of record-breaking events converges to a stationary value under the assumption of constant variance and linear trend (yellow and gray dashed-dotted curve; *Trend ×1, Var ×1* and *Trend×2 abrupt, Var ×1)*. Furthermore, in the case of stationary trends the occurrences of extreme events decrease or increase non-linearly in proportion to the ratio of the linear trend and interannual variability (brown and

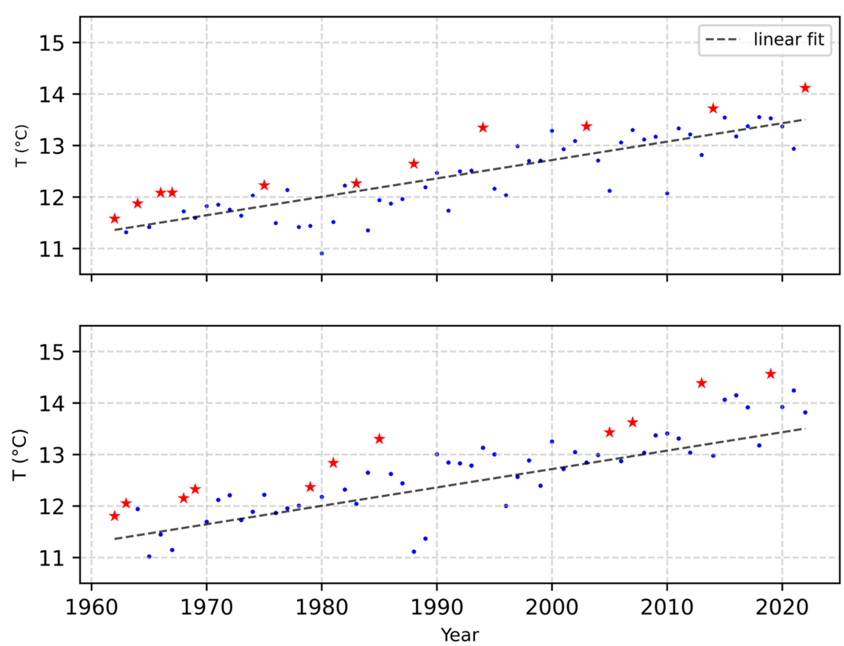

Fig. 2 (**a**) Time series of annual mean surface temperatures for Emilia-Romagna (blue dots) from 1962 to 2022, with the least-square linear trend (gray dashed line); (**b**) randomly generated time series using Monte Carlo. The red stars indicate record-breaking values

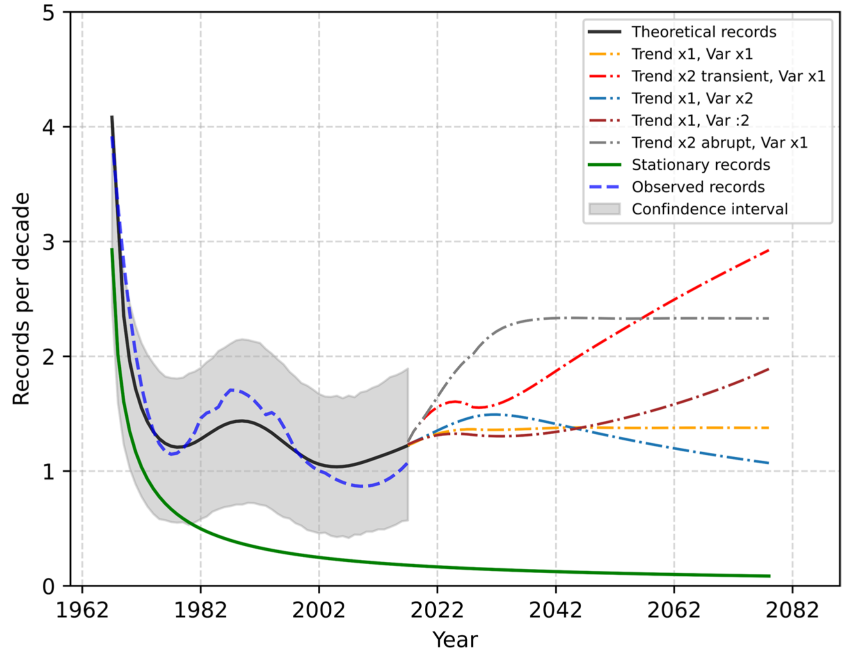

Fig. 3 Records per decade during the historical (1962–2022) and scenario's (2023–2082) periods for the observed time series (blue dashed curve); for the stationary climate assumption (green solid curve), for the analytical solution (black solid curve) during the historical period; for the analytical solution accounting for the idealized scenarios (coloured dashed-dotted lines). The gray shaded areas indicate the 95% level confidence bounds with respect to a Gaussian distribution

violet dashed-dotted curves, *Trend×1, Var ×2* and *Trend ×1, Var:2*), consistently with Rahmstorf and Coumou (2011). A graphical analysis, not presented here, indicates that a linear increase in the standard deviation owed to interannual variability leads to a quadratic decrease in record occurrences. The results in Fig. 3 suggest that the expected number of extreme events increases quasi-linearly with the yearly increase of the trend, as shown by the red dashed-dotted curve. Under the hypothesis of trend with abrupt increase, the theoretical probability of experiencing a record event converges to a stationary value in time after a relaxation time, as depicted by the gray dotted-dashed curve. Furthermore, the comparison between the *Trend ×2 abrupt, Var×1* and *Trend×2 transient, Var×1* suggests that the theoretical occurrence of extreme events is dependent on the warming rate rather than the warming level, consistent with Fischer et al. (2021).

Finally, in Fig. 4 the theoretical framework has been applied to seasonally stratified data over the period 1962–2022, for winter (December, January, and February; DJF), spring (March, April, and May; MAM), summer (June, July, and August; JJA), and autumn (September, October, and November; SON) under the assumption of linear-trend.

The season that yields the majority of decadal records is summer, which exhibits the strongest trend, of 0.48 °C/decade, among seasons. In the last two decades, the increase in summer records driven by the trend is partially compensated by an increase in interannual variability. Spring, in turn, shows the lowest occurrence of annual record-breaking temperatures (e.g., 0.65 records in the last decade). This is reflected by the second lowest linear trend of 0.30 °C/decade and the second highest interannual variability. Furthermore, the amount of theoretical records per decade during spring diminishes drastically under the assumption of non-linear trend (not shown). Under this assumption, during the last decade, the number of records stands at 0.29. This is substantiated by a declining trend observed in the most recent years of the historical period, partially offset by a subsequent increase in short-term interannual variability. This combination of long-term and short-term frequency variabilities justifies also the observation that during the last decades the number of cold events in spring has increased with respect to the first decades of the time series.

4 Conclusions

Global warming has been inducing changes in the frequency of warm and cold-related events since the second half of the twentieth century as documented in Chapter 11 of the latest IPCC report AR6 (Seneviratne et al. 2021). The distribution of land temperatures anomalies and extremes exhibits significant regional and seasonal variability, caused by a number of factors, ranging from large-scale atmospheric patterns variability and local surfaces feedbacks, including those related to land-use changes and emission of anthropogenic aerosols (Kingston et al. 2015; Grotjahn et al. 2016; Drumond et al. 2017; Manzano et al. 2019).

The present study has evaluated changes in mean value and variability in the time series of daily temperatures in Emilia-Romagna from 1962 to 2022 and analyzed the role of long-term trends and interannual variability in modulating the expected number of record-breaking events in the

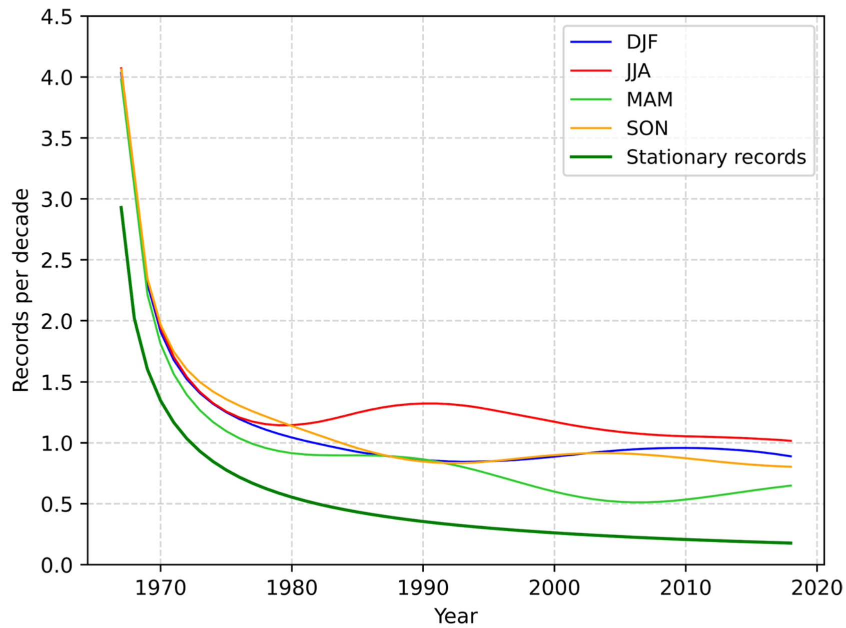

Fig. 4 Records per decade during the historical period (1962–2022) for the analytical solutions during winter (DJF, blue solid curve), spring (MAM, light green solid curve), summer (JJA, red solid curve), autumn (SON, golden solid curve), and for the stationary climate assumption (green solid curve)

corresponding annual mean time series. First, the results show a broadening of the distribution of daily mean temperature anomalies in 1992–2022 with respect to 1962–1991. This result is consistent with previous studies, which focused on the recent positive trends in maximum, minimum, and mean surface temperatures (Tomozeiu et al. 2006; Antolini et al. 2015, 2017). The investigation of the variability of daily surface temperatures within each season suggests a prominent change of seasonal high-frequency variability in 1992–2022 with respect to 1962–1991. During autumn, temperature indices seem less variable in the most recent period, although an increase is found in the amplitude of high-frequency variance. During the period 1992–2022, spring and summer present changes in the high-frequency variability, while during winter only the daily maximum temperatures showed an increase in variance.

A further outcome of this study is represented by the comparison between the theoretically estimated and observed occurrences of record-breaking mean annual temperature events in the last decades. It is evidenced that in the approximation of Gaussian distributed annual temperatures two factors are in play: a long-term trend and short-term interannual variability. A comparison with analytical results obtained for a stationary climate, in which temperature records are modulated by a white-noise-like interannual variability alone, shows that it is very likely that the high number of record-breaking events in the last decade (i.e., 2012–2022) is attributable to the warming trend, rather to natural variability. The probability stands at a value of 86%, which rises to 87% in a context of non-linear trend approximation. These results are consistent with those by Rahmstorf and Coumou (2011) who stated that in highly-aggregated annual mean temperatures time-series characterized by a low variability compared to the warming trend, the majority of the extreme records are due to the trend. This implies that, in the context of future projections, the warming trend is expected to significantly influence the probability of record-breaking annual temperatures. Similarly with Fischer et al. (2021), idealized forcing experiments are implemented for different variability and trend scenarios, and they show that the likelihood of record-breaking events is dependent on the warming rate rather than the warming level. Furthermore, a seasonal analysis has shown that the majority of extreme events are likely to occur in summer rather than in the other seasons.

This work has addressed the role of regional climate change in modulating the statistical properties of surface temperatures in Emilia-Romagna. To enhance the comprehensiveness of this study, it may be advantageous to supplement it with model-based climate projections specific for Northern Italy. This additional data will be provided in a future study and will lead to the estimate of possible future frequency of these extreme events under scenario conditions in the Emilia-Romagna region within the context of studies utilizing Coupled Model Intercomparison Project (CMIP) projections. Nonetheless, the present study constitutes a theoretical framework for interpreting the complex interaction between regional warming and interannual variability and their influence on the frequency of record-breaking annual temperatures.

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Authors contribution **Davide Sabatani:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing.

Valentina Pavan: Conceptualization, Data curation, Formal analysis, Methodology, Resources, Supervision, Validation, Writing – review & editing.

Federico Grazzini: Conceptualization, Data curation, Formal analysis, Methodology, Resources, Supervision, Validation, Writing – review & editing.

Gabriele Antolini: Conceptualization, Data curation, Resources, Supervision, Validation, Writing – review & editing.

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Data availability The datasets analyzed in the current study are obtained from the data available in the ARPAE OpenData portal at the link: https://dati.arpae.it/dataset/erg5-eraclito

Declarations

Permission to reproduce material from other sources The authors declare that there is no material reproduced from other sources.

Competing interests The authors declare no competing interests.

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