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TEMPORAL VARIATIONS OF TRENDS IN THE CENTRAL ENGLAND TEMPERATURE SERIES

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ABSTRACT. *Variations in trend rates of annual values of the Central England Temperature series (CET) over the period 1659-2017 were analysed using moving windows of different length, to identify the minimum period in which the trend expresses a climate signal not hidden by the noise produced by natural variability. Trend rates exhibit high variability and irregular shifting from positive to negative values unless very long window lengths (of 100 years or more) are used. In general, as the duration of the length of the temporal window analysed increases, the absolute range of the trend rates decreases and the signal-to-noise (S/N) ratio increases. The relationship between the S/N ratio and the window length also depended on the total length of the series, so high S/N values are achieved faster when shorter time series are considered. This prevents suggesting a minimum window length for undertaking trend analyses.*

A comparison between CET and the average continental series in the Berkeley Earth Surface Temperature (BEST) database in their common period (1753-2017) repeats the patterns described for 1659-2017, although the average values of the rates, ranges and the "threshold period" in years change, and are more variable in CET than in BEST.

Analysis of both series suggests that the recent warming started early and can be linked to the recovery of temperatures after the Little Ice Age. This process has characterised by progressively increasing trend rates, but also includes periods of deceleration or even negative trends spanning less than 50 years. The behaviour of the two long-term temperature records analysed agrees with a long-term persistence (LTP) process. We estimated the Hurst exponent of the CET series to be around 0.72 and 0.8, which reinforces the LTP hypothesis. This implies that the currently widespread statistical framework assuming a stationary, short-memory process in which departures from the norm can be easily assessed by monotonic trend analysis should not be accepted for long climatic series. In brief, relevant *questions relative to the recent evolution of temperatures such as the distinction between natural variability and departures from stationarity; attribution of the causes of variability at different time scales; determination of the shortest window length to detect a trend; and other similar ones have still not been answered and may require adoption of an alternative analytical framework.*

Variaciones temporales de las tendencias en la serie de temperatura de Inglaterra Central

RESUMEN. *Hemos analizado las variaciones de la tasa de la tendencia de las temperaturas medias anuales de la serie conocida como Central England Temperature (CET) durante el periodo 1659-2017, con el objetivo de identificar el periodo mínimo en el que la tendencia exprese una señal climática no oscurecida por el ruido originado por la variabilidad natural. Las tasas de tendencia exhiben una gran variabilidad e irregularidad cambiando de signo positivo a negativo excepto en ventanas temporales prolongadas de más de cien años. En general, a medida que la duración de la ventana temporal aumenta el rango absoluto de las tendencias decrece y la ratio Señal/Ruido (S/N) aumenta. La relación entre la ratio S/N y la longitud de la ventana depende también de la longitud total de la serie, de manera que se logran valores más elevados de S/N cuando la serie complete es más corta. Estos resultados sugieren evitar periodos cortos de tiempo para estimar o validar una tendencia.*

La comparación de CET y la serie de promedios de temperatura anual continental europea de la base de datos Berkeley Earth Surface Temperature (BEST) en su periodo común (1753-2017) repite los patrones de comportamiento descritos en el periodo 1659-2017, si bien los promedios de las tasas, el rango de las mismas y el periodo umbral en años cambia, siendo más variables en CET que en BEST.

El análisis de las dos series sugiere que el aumento de las temperaturas comenzó hace tiempo y puede asociarse a la recuperación de las mismas tras la pequeña edad de hielo (LIA). Este proceso se ha caracterizado por un aumento progresivo de las tendencias incluyendo periodos de desaceleración o incluso tasas negativas en ventanas temporales de menos de 50 años. El comportamiento de ambas series concuerda con los procesos denominados de larga persistencia (long-term persistence, LTP); el exponente de Hurst de la serie CET calculado oscila entre 0.72 y 0.8, lo que refuerza dicha hipótesis, e implica que las asunciones tradicionales (series estacionarias con escasa memoria), en las que las variaciones puedan ser estudiadas por medio de tendencias monotónicas, no deberían aceptarse en el caso de series climáticas de gran longitud. En resumen, numerosas preguntas relativas a la reciente evolución de las temperaturas, como la distinción entre variabilidad natural de la tendencia climática, la atribución de las causas de la variabilidad en diferentes escalas temporales, la determinación del periodo mínimo de tiempo para detector una tendencia, y otras similares, no han sido plenamente contestadas y podrían requerir la adopción de nuevos enfoques y planteamientos.

Key words: Central England Temperature, climatic trend, climatic variability, signal/noise.

Palabras clave: Temperatura de Inglaterra Central, tendencia climática, variabilidad climática, señal/ruido.

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> The three times - the short, fleeting one of events, conditioned by the intermediate duration of circumstantial cycles, and this by the long, structural time, almost unmoving - which harmonised with and superimposed on each other to clarify the disconcerting unknowns appearing before him.
>
> F. Braudel, *Charles V and Philip II*

1. Introduction

According to the classical theory, intertwined in a time series are the long-term trend, cycles or periodicities, seasonality, and random variability or noise. This analysis framework is relevant for the analysis of the recent evolution of temperature. Assuming the hypothesis that the climate system has short-term memory characteristics, any deviations from the mean climate due to cycles or random variability are rapidly cancelled out by opposing anomalies, so long-term deviations from the norm can only be due to extraordinary causes. Adequate analysis, thus, must enable to separate the noise originated by natural variability related to meteorological processes and cycles related to geophysical or astronomical forcing from the long-term signal (Santer at *al*., 2011), and thus differentiate the part corresponding to a possible human origin (Lennartz and Bunde, 2009; Lloyd, 2015).

The average temperature of the planet has increased by approximately 0.7ºC since the beginning of the 20th century (Allen *et al*., 2015). The evolution of temperature has not followed a steady path, and a sequence of warming, stationary and even cooling phases have occurred when we look at shorter time scales (Easterling and Wehner, 2009). In the context of recent global warming studies, periods of little change or even decreasing temperatures are known as slowdown, global warming pause, or simply hiatus. At present, there is a debate on whether the so-called final global warming hiatus (observed in various datasets since approximately 1998 up to present) exists, as well as in general periods of intense warming or cooling lasting for more than a decade (Foster and Rahmstorf, 2011; Kaufmann *et al*., 2011; Karl *et al*., 2015; González-Hidalgo *et al*., 2016; Medhaug *et al*., 2017; Tung and Chen, 2018). These are some of the reasons for the interest shown in attempting to determine the minimum time span required to detect a long-term trend signal. In climatological terms, this would allow the separation of the trend (signal) from the noise (natural variability and cycles), with a relative contribution from each of these variable components depending on the time scale chosen (De Souza *et al.*, 2013; Münch and Laepple, 2018).

In short-memory time processes, the ratio between signal and noise (S/N) is small in short series but increases rapidly as the series gets larger (Santer *et al.*, 2011). However, there is no agreement on which objective criteria to use in order to determine the minimum span a series must have in order to detect a long-term trend. The relationship between the magnitude of the trend and that of its variability can be a useful criterion (Lennartz and Bunde, 2009; Santer *et al.*, 2011). Santer *et al.* (2011) found that the S/N ratio exceeded the value of one after a minimum of 17 years in their study of the period from 1979-2010. Lohele (2009), Lennartz and Bunde (2009), and McKitrick (2014) suggested as a criterion to use the minimum period in which the two confidence intervals of the trend are positive. In his analysis of the HadCRUT4 series, McKitrick (2014) determined it at a minimum of 19 years, and between 16 and 26 years in the series of the lower troposphere temperature provided by satellites. However, several questions remain without a definite answer such as what is the long-term signal in the record of recent surface temperatures; what proportion of this depends on the various forcings; and what is the minimum time period required to detect a warming signal (Cohen *et al.*, 2012).

On this article, we analyse the temporal variability of long-term trends in annual mean temperatures, and we try to determine the minimum period in which an unequivocal climate change signal can be detected. We apply the moving windows method for periods of 10 years or longer to the Central England Temperature (CET) dataset, spanning the 1659-2017 period. In the common period 1753-2017 we compare this series with the regional series of Europe from the Berkeley Earth Surface Temperature (BEST) database (Rohde *et al.*, 2012).

2. The Central England Temperature (CET) data

CET consists of a sequence of records from several locations in the central sector of England, which taken together comprise the longest instrumental temperature record on Earth. The series is a reasonably good representation of conditions in the British Isles (Croxton *et al.*, 2006), and its compilation, quality control and uncertainty at different periods are described in Manley (1953, 1974), Parker *et al.* (1992), Parker and Horton (2005), and Parker (2010). CET is available in daily and monthly data versions on the official website of the Climate Research Unit, at https://www.metoffice.gov.uk/hadobs/hadcet/data/download.html. The monthly averages cover the period from 1659 to the present; the version with maximum and minimum monthly averages is shorter and starts at the end of the 19th century.

The manifest opportunities offered by the CET dataset make it one of the most analysed temperature series. Among others, Plaut *et al.* (1995) attributed its initial low values (around 1°C less than the present) to the end of the Little Ice Age (LIA), also known as Maunder minimum. They pointed out that recent temperature rise started around 1985, rather late as compared to the world averages, with possible relationships with ENSO in the 7-8 year and 15-25 year cycles. Balliunas *et al.* (1997) observed that the start and length of the period of analysis had an enormous effect on the magnitude and variability of computed trends. They detected a 0.3°C per decade cooling period between 1659 and 1720, which they too related to the LIA. The same authors concluded that the temperature rise started early around 1860, and warned that long-term series derived from climate models were not able to reproduce the fluctuations present in the series. Benner (1999) studied the period 1659-1997 and also related the first few years in the series to the end of the LIA, locating the origin of recent temperature rise at the start of the 19th century. This author also identified cycles similar to those mentioned by Balliunas *et al.* (1997), observing that they were not regular, and suggested that fluctuations in CET depended, above all, on the evolution of solar activity and the pattern of the North Atlantic Oscillation (NAO), with no apparent link to the ENSO, in contrast to Plaut *et al.* (1995). Recently, the relationships between CET and solar activity variability have been re-analysed by Gruzdev and Bezberkhnii (2019).

Harvey and Mills (2003) described non-linear behaviour in the trends between 1723-1999, with successive phases of cooling, stability and warming, without finding any evidence of a net global increase or an accelerated rise in temperatures in the 20th century, except in spring. De Souza *et al.* (2013) studied the multifractal nature of the series using 11-year moving windows. They found that multifractal characteristics changed in time, meaning that the series variability changed according to periods, which agrees to a certain extent with results from Benner (1999) and Baliunas *et al.* (1997). Proietti and Hillebrand (2013) returned to the study of the seasonal behaviour of CET, detecting a possible advancement in spring, similar to observations made by Harvey and Mills (2003). Finally, Karoly and Scott (2003) and King *et al.* (2015) suggested that recent evolution of CET was influenced by human CO2 emissions.

It is evident that all these studies have a regional bias and that extrapolation of their conclusions to other areas should only be done taking this into account. However, it is also true that the series provides a unique record of thermal evolution in mid-latitudes, the only one possible with observed data, including the most recent period, and whose length enables a study of the relationship between variability and an assessment of the trend in various periods and time windows.

3. Methods

From the original monthly time series, we calculated the annual mean value of CET as usual in climatological studies (December to November). We converted the series of annual mean temperature into a series of anomalies by subtracting to each annual value the average of the entire period. We then analyzed variations in the linear trends obtained using a moving window approach. That is, a window of specified length was moved over the data, year by year, and trend analysis was performed on the data in the window. This analysis was repeated for increasing window lengths, starting from a minimum length of 10 years (resulting in N=348 moving windows) to a maximum of 357 years (resulting in N=1 moving windows). For each window size we determined: (i) the signal, as the average of the linear trend rates obtained for all moving windows; (ii) the absolute range of these trend rates; (iii) the frequency of moving windows with positive and negative trends; and (iv) the signal to noise ratio, defined as the ratio between the average of the linear trend rates and the range of the 70% of trends (i.e., excluding the 15% higher and lower values).

Computation of linear trends is the most common method for analyzing temperature change (Foster and Rahmstorf, 2011), and therefore it has been used on many studies (Liebmann *et al*., 2010, among many others; see recent examples in Fyfe *et al*., 2016, and Sun *et al.,* 2017) and on the reports of the Intergovernmental Panel on Climate Change (IPCC). Many authors used ordinary least squares (OLS) regression to calculate trend rates and significance, implying accepting the usual assumptions of OLS on the residuals of the regression: linearity, equal variance, independence, and normality. Many have argued that it is not realistic to use OLS with climate data, due precisely to these constraints. In particular, it is not realistic to assume independence of the residuals, i.e. that the observations are uncorrelated. In our case we used a modified version of the Mann-Kendall non-parametric test, which is a distribution-free approach, which includes pre-whitening to eliminate the influence of auto-correlation (Yue *et al*., 2001). This implies assuming that the CET record exhibits short-term persistence, and in particular an AR1 model is used in which the autocorrelation function is limited to the previous record. The magnitude of change or trend rate was calculated with the non-parametric Theil-Sen estimator (Sen, 1968),

To estimate the noise, i.e. the uncertainty in the trend estimation, we followed the approach by Santer *et al*. (2011), explained by Rapp (2014, pp. 194 and following, and 439 and following). For each time window the absolute range of all the trend magnitudes obtained was multiplied by 0.70. The value of 0.70 arises from the assumption of Santer *et al*. (2011) that trend rates follow a normal distribution at any given temporal window, so that a range of 70% would include 95% of the cases. In our case this multiplicative factor only was used for comparison between different windows lengths and for comparison with previous analyses, and no test about normality of the inferred rates was performed.

The CET series cannot possibly be compared with any other because of its length; therefore, to evaluate its results, we repeated the analysis with the regional temperature series for Europe from the BEST database (Rohde *et al*., 2013; official website http://berkeleyearth.org/data/). The analysis was carried out for the overlapping period between the two datasets, 1753-2017, as well as for two sub-periods: 1853-2017 and 1953-2017, to observe whether the total length of the series affected the results.

4. Results

4.1. Period 1659-2017

Figure 1 shows the evolution of the annual temperature anomalies in the CET for the 1659-2017 period. Overall, the average annual temperature in the CET series has increased by 0.94°C in 357 years, or a mean rate of 0.028 °C per decade (°C d^{-1} from now on). As a whole, the series yields a positive long-term trend signal, although with successive periods of increase and decrease.

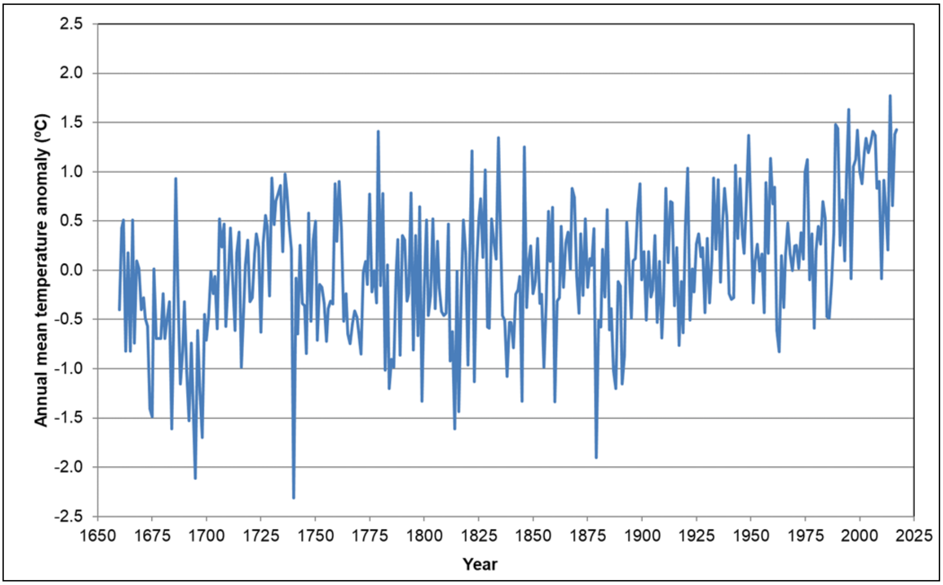

Figure 1. Annual mean value of Central England Temperature serie (1659-2017). Values as anomalies over the entire period.

Table 1 shows, for selected window lengths spanning between 10 and 200 years, the average trend rates, the extreme values, the absolute range, the signal to noise (S/N) ratio, and the number of time windows (periods) obtained. Complete results considering all the window lengths analysed are provided in the Annex. Figure 2 shows the variation of the average trend rates and the absolute range for all time window lengths considered.

Table 1. Statistics of trend rates by length of the time windows in the CET series (1659-2017). Values in °C per decade (°C d^{-1}).

	Length of the window in years											
	10	20	30	40	50	60	70	80	90	100	150	200
Average	0.023	0.048	0.052	0.049	0.046	0.040	0.035	0.030	0.027	0.025	0.019	0.018
Max.	1.733	0.894	0.456	0.387	0.369	0.260	0.207	0.148	0.122	0.104	0.073	0.051
Min	-1.790	-0.636	-0.400	-0.272	-0.194	-0.161	-0.097	-0.070	-0.079	-0.059	-0.021	-0.007
Range	3.523	1.530	0.856	0.659	0.563	0.421	0.304	0.219	0.202	0.163	0.094	0.058
S/N	0.009	0.044	0.087	0.106	0.117	0.137	0.166	0.199	0.192	0.217	0.291	0.446
n	348	338	328	318	308	298	288	278	268	258	208	158

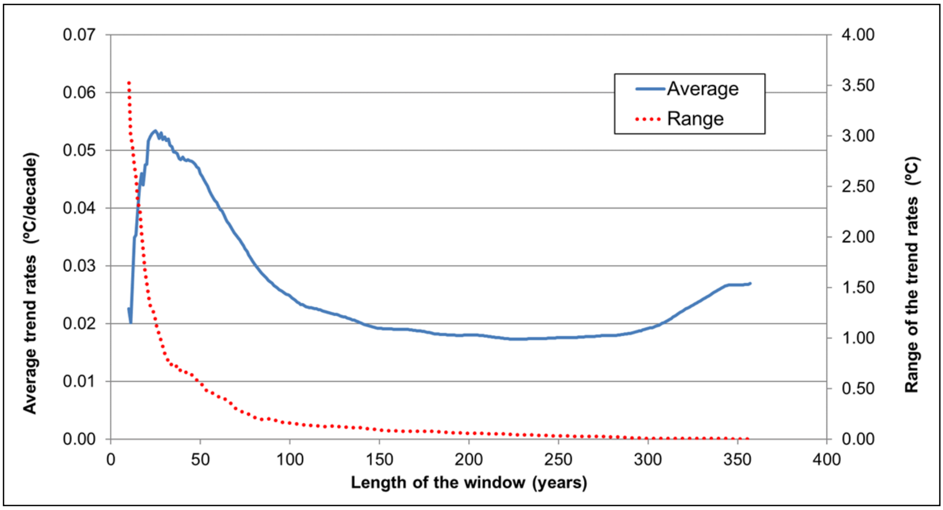

Figure 2. Variation of the average and range of trend rates (°C d^{-1}) as a function of the length of the window (in years).

The average trend rates vary with the length of the period selected, but the relationship is not monotonic: the rates increase from the 10-year window to a maximum of 0.053 °C per decade at 25 years and falls as the length of the temporal window increases. The absolute range of the trend rates is inversely proportional to the length of the time window used, and the signal-to-noise ratio shows the opposite effect. The absolute range of the trend rates decreases exponentially as the length of the temporal windows increases. For window lengths shorter than approximately 50 years, the range is one order of magnitude larger than the average trend rate. It can be considered that stability is only reached for very long window lengths of over a century.

Throughout the series, the sequence of periods with positive and negative trends varies, depending on the window length. Table 2 shows, for a number of window lengths, the number of periods according to the sign of the trend, and the percentages. Figure 3 shows the proportion of windows with positive and negative trends, for window lengths between 10 and 250 years. Complete values are provided in the Annex.

Table 2. Number of moving windows with a positive or negative trend and the percentage, for a selection of window lengths.

	Length of the window in years											
	10	20	30	40	50	60	70	80	90	100	150	200
Positive	186	195	205	200	210	210	216	211	212	208	172	125
Negative	162	143	123	118	98	88	72	67	56	50	36	33
Positive (%)	53	58	63	63	68	70	75	76	79	81	83	79
Negative (%)	47	42	38	37	32	30	25	24	21	19	17	21

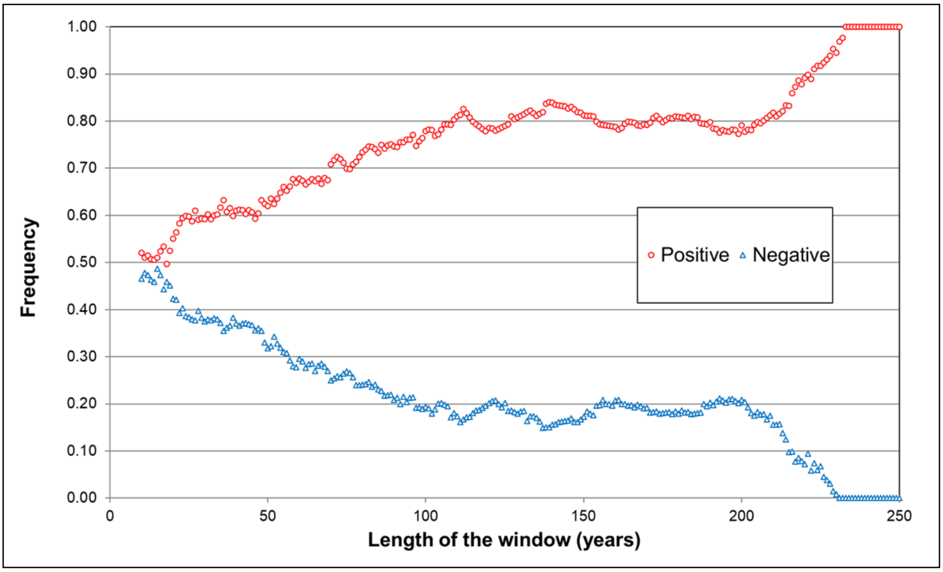

Figure 3. Frequency of the number of periods with positive or negative trends, according the length of the window (in years).

For window lengths lower than 23 years, the proportion of positive and negative trend rates is higher than 40%. Although positive trends predominate for all window lengths, periods of over 100 years are required for values higher than 80% to prevail. No time windows with negative trends were detected for window lengths larger than 231 years.

Figure 4 shows the variation of the signal to noise ratio (S/N) as a function of the window length. Low S/N values indicate very high noise in the determination of the mean trend rate, and vice-versa. The Figure includes the variation of the rate average (as in Fig. 1) for a reference. The highest trend rates obtained with relatively low window lengths are associated with low S/R values, and the trend signal becomes more reliable as the period increases.

In no case does the S/N ratio reaches values above 1. S/N value of 1 means that the magnitude of the noise is equivalent to that of the signal. In the CET series, an S/N ratio of 0.1 is reached for a window length of 35 years (average trend 0.05 and range 0.711) and a window length of 118 years is required for an S/N ratio above 0.25 (average trend 0.022 and range 0.124). If one wants to have positive values at both ends of the range, so there is high certainty that the average trend rate is positive, a window length of 231years is required. These results suggest that the noise in the CET annual average series is very high. In any case, trend rates for window lengths of less than three decades should not be accepted as a climatic signal in the CET, since they include very high variability, and at least five decades can be cautiously suggested to achieve a relatively good certainty level.

Figure 4. Variation of the signal to noise (S/N) ratio according to the length of the window (in years). The figure includes also the average trend rate per window length.

4.2. Time variations in the rate

Figure 5 shows the time variation of trend rates computed using the moving window approach for five selected window lengths. The values in the ordinate axes indicate the starting year of each moving window, allowing comparing moving windows of different lengths since they share the same starting year. As expected, the time variability decreases as the window length increases. The time series of trend rates for a ten years window length is very noisy and shows rapid changes between positive and negative trends, that are mostly not significant in the Mann-Kendall test. In the second window length, 25 years, the temporal variability continues to be high. For these two window lengths, there does not appear to be a global guideline in the sequence of periods with positive and negative trends. Indeed, the frequency of positive and negative windows always exceeds 40% (Table 2 and Fig. 3), and the frequency of periods with significance is less than 15%.

The longest window lengths allow for patterns to be easily detected, displaying a long-term signal expressed by a high frequency of periods with statistical significance and a positive sign. In the 50-year window length plot, and especially in the 100 and 150 years, an initial cooling phase (negative trend rates) is detected since approximately 1700 until the moving windows starting approximately in 1750. From then on, there is a general increasing trend until the present. Occasionally, intermediate cooling pulses (negative trend rates) are detected, at least in the 50-year and 100-year window lengths, but not in the 150-year one.

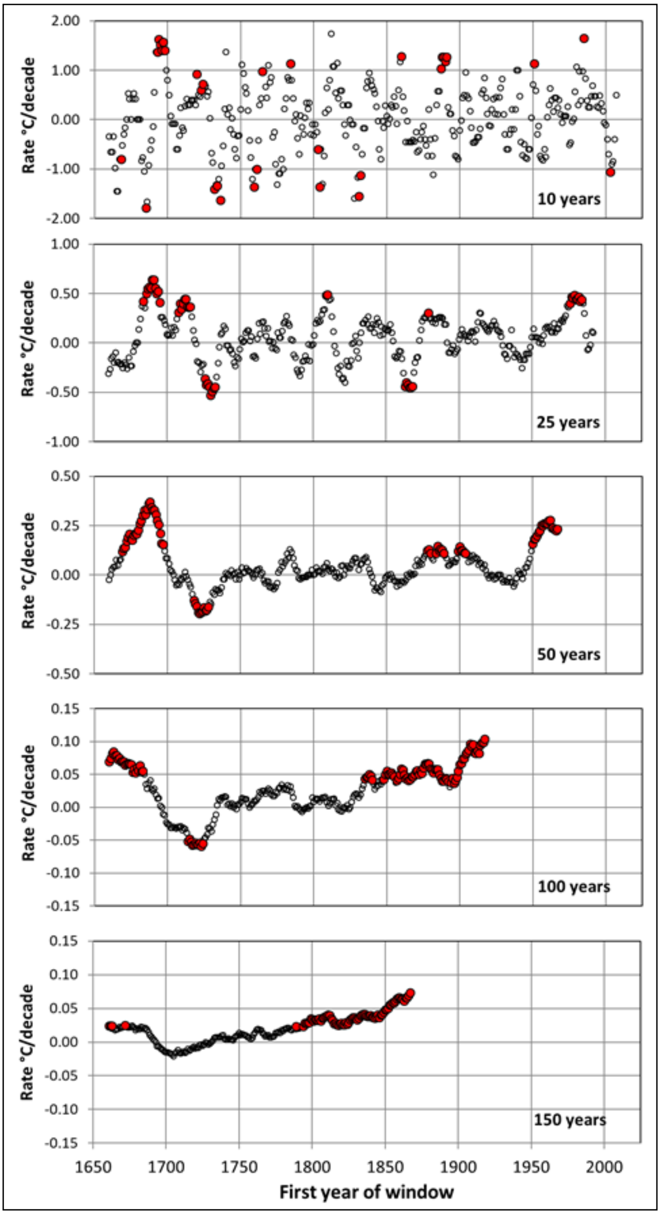

Figure 5. Evolution of the trend rate for moving windows of different length (in years). Values in °C d^{-1}. Colored symbols significant (p 0,05).

In conclusion, the longest window lengths demonstrate that, since the first decades of 1700, there has been a gradual rise in the average annual temperatures in the CET. It is also interesting to note that the magnitude of the rates estimated in the most recent

50-year windows (i.e., starting approximately in the centre of the 20th century) are lower than those estimated at the start of the series.

A study of the statistical significance of the trend rates reinforces this interpretation. All the trends computed using moving windows of length 100- and 150-years are significant from 1835 and 1794, respectively. For the 200-year window length (not shown in the Figure) the trends are significant from 1738. For a window length of 50 years, only the moving windows starting between 1899 and 1904 and between 1950 to 1967 are significant. To give another example, for a window length of 75-years (not shown) only the moving windows starting between 1869 and 1889 and between 1927 to 1942 are significant.

4.3. Comparison between CET and BEST

A major problem in any analysis of the complete version of CET is the impossibility of making comparisons since there are no synchronous records of the same length. Therefore, we reduced the period of analysis to 1753-2017 to match the global continental series from the BEST database. Figure 6 shows the two series expressed as anomalies, while Figure 7 shows the annual difference between both. The highest variability among years of the CET series is evident, as it could be expected from the comparison of a record at a single site and a regional average. The exception to this is the first two decades of the record when the BEST series also exhibits large variability. Despite a general good coincidence between the two series, there is a systematic bias between them, as evidenced by the temporal evolution of the annual differences. The CET series tends to be warmer than BEST in the first half of the study period, and colder in the second half. This bias follows an almost perfect linear trend, with mean values of +0.17 and -0.19 ºC at the extremes of the study period.

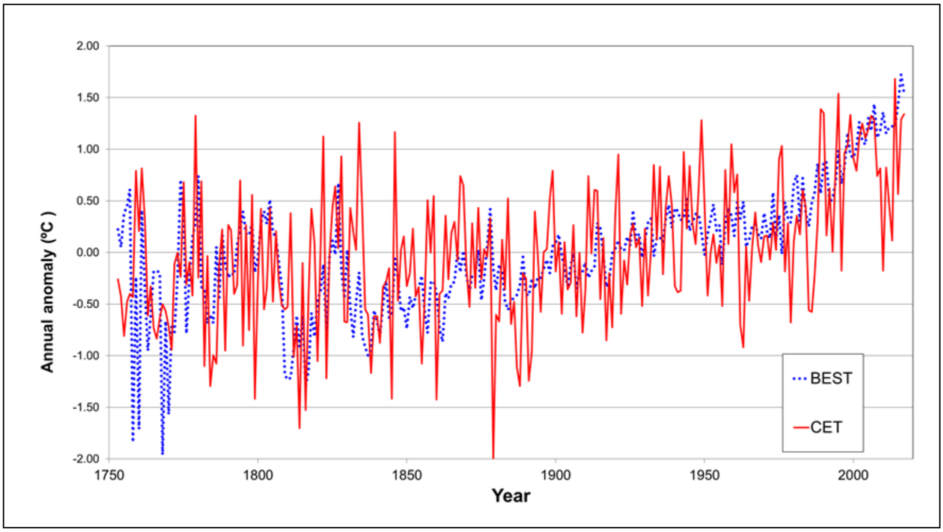

Figure 6. Evolution of the average annual temperature in BEST and CET for 1753-2017. Values in anomalies respect the entire period.

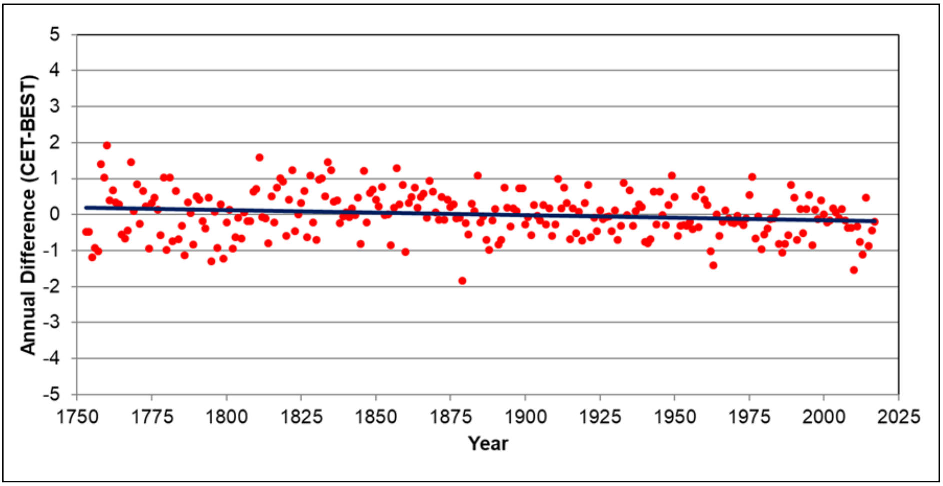

Figure 7. Annual difference between CET and BEST of the average temperatures. Values in °C.

The global results from analysing both series in selected window lengths are shown in Table 3 (annual data in the Annex).

Table 3. Description of the CET and BEST series for 1753-2017. Values in °C d^{-1}.

Length of the window in years															
		10	20	30	40	50	60	70	80	90	100	125	150	175	200
BEST	Average	0.112	0.094	0.078	0.064	0.053	0.045	0.044	0.045	0.046	0.048	0.053	0.055	0.057	0.057
CET	Average	0.042	0.057	0.057	0.050	0.044	0.039	0.036	0.035	0.035	0.034	0.033	0.031	0.032	0.033
BEST	Range	3.306	1.679	0.963	0.674	0.476	0.366	0.298	0.233	0.204	0.175	0.130	0.094	0.071	0.049
CET	Range	3.333	1.348	0.822	0.474	0.366	0.254	0.221	0.149	0.122	0.111	0.094	0.069	0.050	0.029
BEST	S/N	0.048	0.080	0.116	0.137	0.158	0.178	0.212	0.276	0.325	0.396	0.581	0.838	1.151	1.662
CET	S/N	0.018	0.060	0.099	0.151	0.172	0.217	0.235	0.340	0.407	0.442	0.502	0.649	0.922	1.613
	n-win-dows	255	245	235	225	215	205	195	185	175	165	140	115	90	65

As a consequence of the bias that we just described, the average trend rates tend to be higher in BEST than in CET (Fig. 8). In BEST, it decreases as the length of the window increases, at least up to 50 years, and varies between 0.11 and 0.04 °C d^{-1} for the 10 to 100-years window lengths. In CET, however, they rise slightly among the 10-to 30-year window lengths, and fall in the longer ones, with variations between 0.03 and 0.06 °C d^{-1}. Over the complete period, the trend rates obtained for 1753-2017 are higher for BEST (1.58 °C) than for CET (1.0 °C).

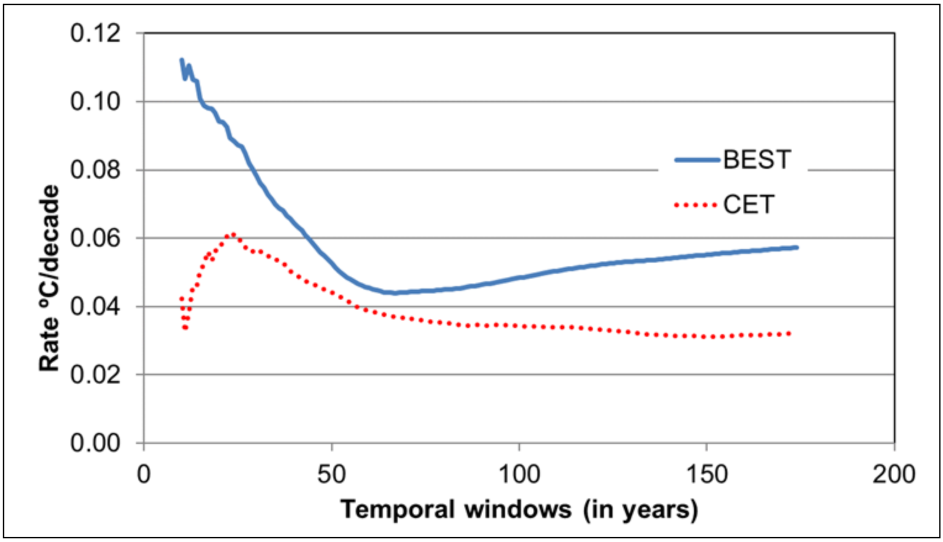

Figure 8. Average mean annual temperature trend rate depending on the length of the window in years. Values in °C d^{-1}. Common period for CET and BEST (1753-2017).

The behaviour of the range of trend rates depending on the window length is more similar between the two datasets, although the range is slightly higher in BEST than in CET (Fig. 9). In both series, the range falls exponentially as the window length increases. In BEST, the range of trends is 0.17 °C d^{-1} at around 100 years of length, 0.05 °C d^{-1} at 200 years, while for the same window lengths the range in CET is 0.11 °C d^{-1} and 0.03 °C d^{-1}, respectively.

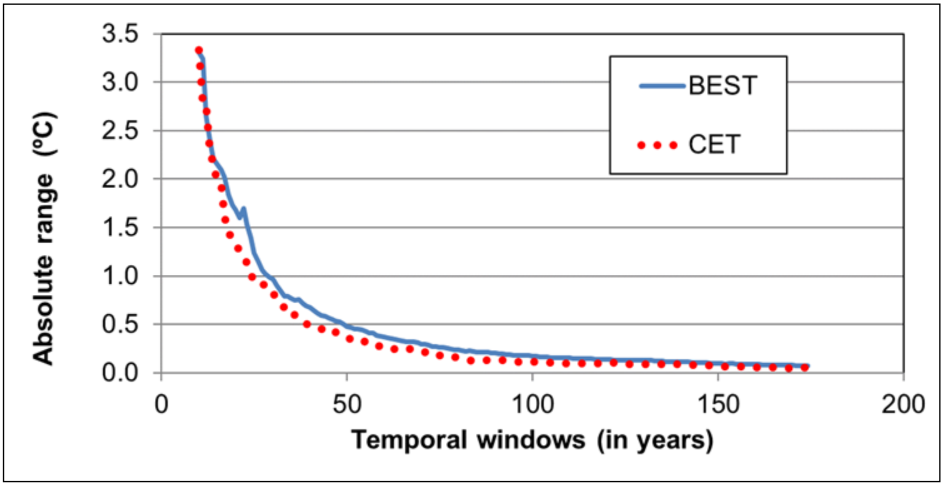

Figure 9. Variations in the absolute range (°C) of average annual temperatures rates by the length of the window in years.

Figure 10 compares the signal to noise ratio (S/N) in both datasets. Both series exceed the threshold of 1 in windows longer than 150 years, slightly earlier in BEST (167 years) than in CET (182 years). Similarly, in BEST the two intervals at either end of the range are positive in the 145-year window, and in CET this occurs at 135 years. The Figure shows that BEST behaves in a much more uniform manner than CET as the time window increases, since in CET the S/N ratio is constant at around 0.5 in a sequence of windows between 100 and 140 years in length.

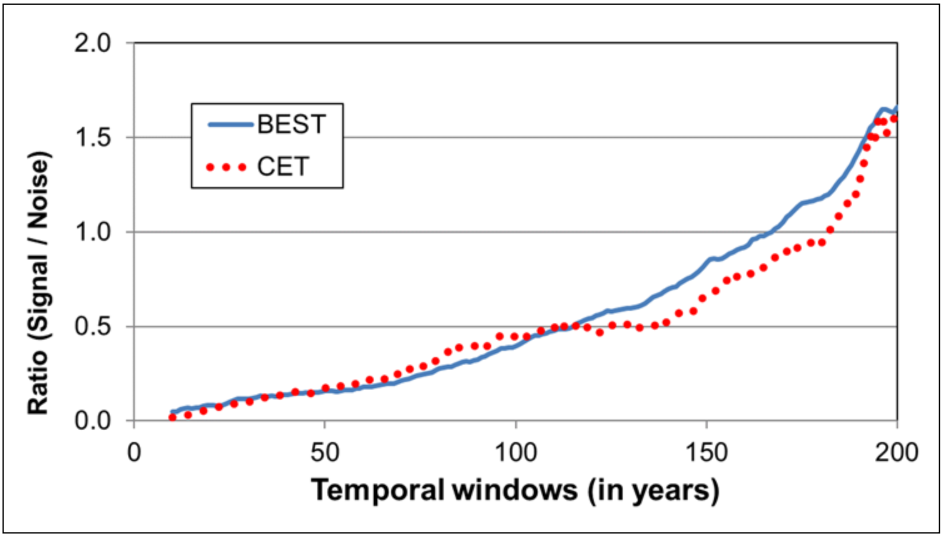

Figure 10. Variations in the S/N ratio depending on the length of the window in years. Period 1753-2017.

The frequency of periods with positive or negative trends, depending on the window length, is given in Table 4. In both series, in about 1/5 of the moving windows analysed for window lengths of less than 50 years trends with a negative sign are constant, and this does not change until reaching window lengths of 125 years or more when only positive trends are found.

Regardless of the differences between the two series, the results suggest that trend variability in short periods is very high and, therefore, any conclusion based on, and analysis of, the same should be considered carefully. The signal to noise ratio expressed by the S/N is lower than one for several windows lengths, thus emphasising that the two series contain significant noise.

Table 4. Frequency and percentage of periods accordingly temporal windows by trend sign in BEST and CET 1753-2017.

Length of the window in years														
	10	20	30	40	50	60	70	80	90	100	125	150	175	200
CET_Positive	137	150	157	145	155	153	171	164	160	154	138	115	90	65
CET_Negative	118	95	78	80	60	52	24	21	15	11	2	0	0	0
BEST_Positive	174	177	181	175	177	163	158	144	132	123	113	115	90	65
BEST_Negative	81	68	54	50	38	42	37	41	43	42	27	0	0	0
BEST_Positive (%)	68	72	77	78	82	80	81	78	75	75	81	100	100	100
CET_Positive (%)	54	61	67	64	72	75	88	89	91	93	99	100	100	100
BEST_Negative (%)	32	28	23	22	18	20	19	22	25	25	19	-	-	-
CET_Negative (%)	46	39	33	36	28	25	12	11	9	7	1	-	-	-
n-windows	255	245	235	225	215	205	195	185	175	165	140	115	90	65

Finally, Figure 11 shows the temporal variability of trend rates for given window lengths obtained from BEST. Variability is generally lower in BEST than in CET (see Fig. 5) in any of the examples. For small window lengths of 10 to 25 years there is a significant reduction in the inter-annual variability since the mid-19th century, a fact not observed in CET.

As it was the case with the CET, in the 50-year window lengths and higher, the temporal variability is lower and more evident patterns arise. In the BEST series, an initial cooling phase is found with negative trends around 1750-1800, a second phase with oscillations but with positive values, and a period of decreasing (but positive) rates as the 19th century gave way to the 20th, and a final phase of uninterrupted increase in the trend magnitudes.

However, the most interesting result is undoubtedly found in the longer window lengths. In the 100- and 150-year time windows, the secular context of the two series emerges, and both the global (BEST) and the regional (CET) series show that the recent upward trend of temperatures can be traced back to the mid-18th century. The increase has not been monotonic and periods with decreasing trend rates have occurred, but the trend rates have always been positive and, in general, increasing over that period.

One striking result of the signal-to-noise ratio relationship to the window length is the substantial difference that exists between the analyses using the complete CET series (1659-2017, Fig. 4) and the reduced one (1753-2017, Fig. 10). These differences suggest that the S/N ratio, as well as being determined by the window length, might also be affected by the total duration of the series. To this end, we analysed the S/N ratio in the two datasets (CET and BEST) using shortened versions of each series (Fig. 12).

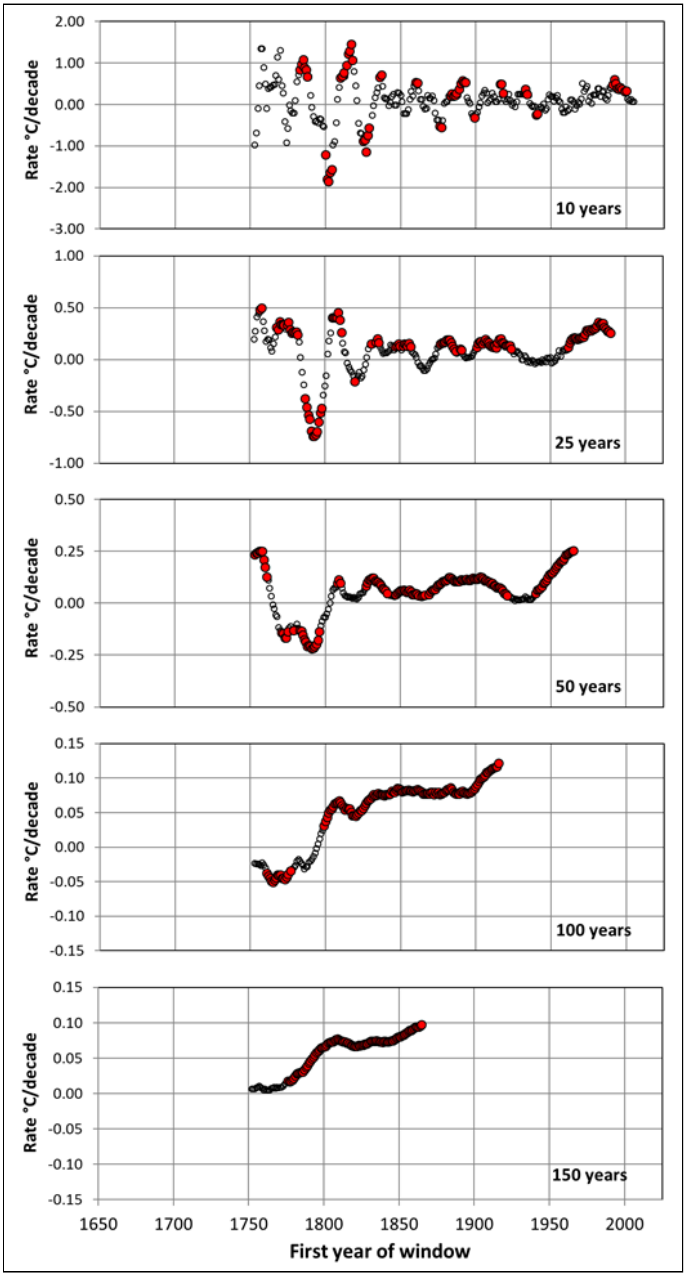

Figure 11. BEST Europe continental series. Evolution of the trend (Sen rate) in windows of different length (1753-2017). Values in °C d^{-1}. Colored symbols significant (p 0.05).

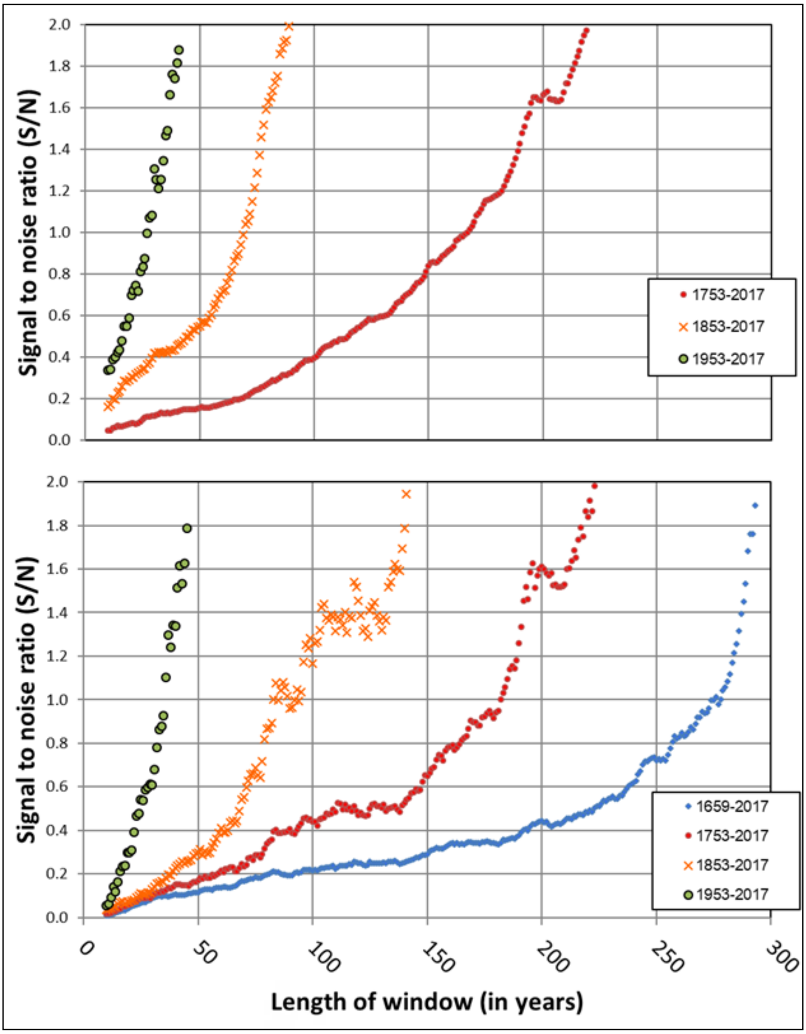

Figure 12. Variations in the S/N ratio in CET and BEST annual temperature mean values depending on the total length of the series. BEST above, CET below.

It is interesting to notice, in both datasets, that shorter periods (e.g., 1953-2017) show a steeper evolution of the S/N ratio. In other words, for a given window length the S/N ratio is in all cases higher for shorter series. Thus, in the CET version for 1953-2018 an S/N ratio of one is achieved with a window length of around 29 years, but this value increases to 82, 162 and 278 years in the CET versions starting in 1853, 1753 and 1659, respectively. The same pattern is found in all three versions of the BEST series, although an S/N ratio of one is reached with shorter window lengths than in CET (27, 69 and 163 years, respectively).

5. Discussion

Science must answer two fundamental questions related to recent temperature rise: its physical causes and its future evolution. Regarding the causes, discussion on the contribution of human emissions to the recent evolution of climate has not ended. The discussion does not focus so much on whether the emissions affect or not, but on quantifying this effect. As for the second question, most climate models suggest a higher increase in temperature than observed (Stockwell, 2009; Lüdecke *et al*., 2011; Cohen *et al*., 2013; Fyfe *et al*., 2013), and so the nature of the recent hiatus is still under discussion to decide whether or not it is part of the natural variability (Schmidt *et al*., 2014; Trenberth *et al.,* 2014; Meehl, 2015; Li and Zha, 2019). Consequently, the disparity between models predictions and the observed data could be due to problems arising from the forcing included in the models (emissions, among others, see Fyfe *et al*., 2013), the climate sensitivity used (Lewis and Curry, 2015), the possible persistence, or a combination of all these factors (Cohn and Lins, 2005). For these reasons, extrapolating linear trends *ad futurum* does not seem to provide the most suitable solution (Rapp, 2014) and the results from this study seem to point in that direction.

5.1. General points

In the debate on the recent temperature rise and its causes, it is becoming increasingly important to include the length of the period analysed. The reason for this is simple: it is accepted that the value of a trend is more reliable the longer the period analysed, arguing that this is the way to reduce noise, and thus uncertainty.

In general, trend rates are more variable when looking at short time windows, a fact observed in the complete CET series and also in the common period for CET and BEST. Shorter time windows not only have the largest variability, but they also give rise to more frequent periods with both positive and negative trends, whose proportions only become predominantly positive (more than 80% of the total) for window lengths of 100 years or more in the complete CET series, and over 50 years in the shortened versions of CET and BEST (1753-2017). In the shared period, both series indicate that rates calculated with window lengths of less than three decades are subject to high variability, and lengths of more than fifty years are required to arrive at some stability, at least in the trend sign. In addition, we found that stability is reached later in the CET series than in BEST.

Together with the period length, our analysis shows that the signal to noise ratio, and therefore the uncertainty of the trend rate, also depends on the length of the total period of analysis. We found that, for a given window length, the signal-to-noise ratio can have very different trends. The temporal evolution of trend rates using the moving window approach displays similar patterns in CET and BEST, with higher variability related to shorter window lengths and positive signal leading to increased and sustained warming from the start of the 19th century. We also detected a change in variability in BEST which is not identified in CET, which could very well be related to the variation in the number of observatories used to construct the BEST series. Further exploration is needed about such point, although this appears as the most plausible explanation.

Lastly, it is difficult to establish the minimum window length in which the signal to noise ratio is small enough to provide confident trend estimates. This is so because the S/N ratio not only varies with (i) the duration of the selected period (window length), and (ii) the specific period-analysed (starting year) but also (iii) the length of the complete series under study. The general suggestion by Loehle (2009), Liebmann *et al.* (2010), and Santer *et al.* (2011) to analyze series of at least 20 years long in order to obtain a S/N ratio larger than one should be challenged, since in both CET and BEST we have found that very low S/N ratios can prevail even for much longer window lengths if the total series is long enough. In particular, in the longer versions of each series, we found that the reduction of the S/N ratio as the window length increased occurred at a very slow rate as compared to the shortened versions of the series. This implies that an apparent reduction of the noise could be achieved by merely reducing the period of analysis. However, that would be more an artefact derived from the length of the period than from a real process. For the same reason, linear trend models should not be applied to prolonged periods, nor to estimate the trend of the complete series, or make extrapolations to predict the future. The conclusion is that all trend analyses should be put in a time context in order to justify any attribution.

5.2. Secular context

In our analysis and preceding discussion, we have assumed that a stochastic process with short-term persistence (STP) is an adequate model for long temperature records such as the CET. STP means that each data point is correlated only with a limited number of previous records, i.e. that the autocorrelation decays exponentially with the time lag. However, some authors have claimed that climate records are better represented by long-term persistence (LTP, also known as long-range memory) processes (Cohn and Lins, 2005; Lennartz and Bunde, 2009). As opposing to STP, LTP implies that autocorrelation decays much more slowly, so correlation persists up to much longer time lags.

LTP in a time series can arise from multiple forcing acting on different time scales, as it is the case of the climatic system. The consequences of LTP on time series are variability over different time scales and trends irregularly shifting from positive to negative, as well as more frequent clustering of anomalous events. Due to the complexity of the climate system and its non-linear behavior, if LTP is detected in a temperature series, it would not be necessary to assume that there is an external forcing to understand changes such as those found in recent decades, which could be justified by natural variability. For these reasons, Zorita *et al.* (2008) insisted that values recorded in recent decades do not necessarily point to extraordinary cases in a time context. In general, LTP makes the identification of long-term trends much more difficult, and in particular attribution to human-induced emissions more complicated.

LTP is usually identified by the Hurst exponent (H). H takes values between 0 and 1, with values higher than 0.5 indicating LTP. Lennartz and Bunde (2009) found that values of H oscillated around 0.65 for continental temperature series. Lüdecke *et al.* (2011) studied 2249 series from the GISS database observatories for the period 1906-2005, and found values of H about 0.60 and 0.65. They also estimated the probability that the observed recent trend had a natural origin between 43% and 90%, in which case the contribution from humans would be marginal. Markonis and Koutsoyiannis (2013) reviewed several instrumental and proxy temperature series and suggested a much value of H of 0.92 or even higher. We estimated the value of H exponent in the CET following different approaches, and found that it ranged between 0.72 (following the original R/S analysis of Hurst, 1951); 0.78 (corrected R/S method, Weron, 2002); to even 0.80 (via spectral regression, Robinson, 1994). These results support the hypothesis of LTP in the CET, and therefore help to explain the variability at different time scales found in our analysis. LTP would also help to explain the otherwise surprising result of the much faster increase of the S/R ratio when the length of the entire series was reduced, that we also found in the BEST series.

However, it is one thing to accept that the temperature in recent decades occurs within the frame of a centennial trend or even longer-term processes, and quite another to identify its origin (Cohn and Lins, 2005). Several authors state that, following the cooling detected at the end of the 18th century, there have been signs of warming in CET since the mid-19th century (Plaut *et al*., 1995; Baliunas *et al*., 1997; Benner, 1999). Our analysis suggests an even earlier date as the start of the recent warming phase since, when using longer window lengths (100 to 150 years), the trend rates are always positive since around 1750. These early dates suggest that the temperature increase observed in the 20th century is partly the recovery of temperatures following the Little Ice Age, and that this is the secular context in which the present should be analyzed and understood.

The comparative analysis between the CET and BEST series shows that the variability of temperature trends is higher in the local series record than in the regional averaged series, in agreement with previous studies (Lennartz *et al*., 2009). This does not prevent patterns common to both series from being observed, particularly the positive behavior shown by their trend rates in window lengths of more than 75 years. The coincidence with the BEST series suggests that the CET series captures the regional behavior of temperatures adequately. Thus, CET would represent the longest instrumental record in which to insert the general evolution of the temperatures on the planet contained in BEST.

6. Conclusions

We studied the variability of trend rates of annual temperature anomalies in the CET series over the period 1659-2017 using moving windows of different length.

We found that trend rates exhibit substantial variability over different time scales, and irregularly shift from positive to negative. Only for very long window lengths of 100 years or more a consistent positive trend signal is obtained.

Using such long window lengths, our results suggest that the recent warming started at an early date around 1750, linking it to the recovery of temperatures since the end of the Little Ice Age. Since that date, the trend rates follow an increasing path, although periods of deceleration or even negative trends are observed at shorter window lengths.

Our results do not allow for a definitive suggestion on a minimum window length required to detect a clear climate signal where noise does not predominate. This is so because the signal-to-noise ratio (S/N) depends not only on the window length, and selected years, but also on the total length of the series under study. A cautious estimate points to minimum periods of 30 to 50 years. Given that the increase in the S/N ratio with the window length is progressively reduced as the length of the total series increases, linear estimates of the trend should not be applied to very prolonged periods such as the CET.

In light of our results, an open question remains regarding the most appropriate statistical model for the analysis of temperature (or other climatic) series. Most climatic analyses assume a short-term persistence process (STP) or even a random process (white noise), but our analysis of the CET series reveals behaviour, which corresponds better to a long term persistence (LTP) process. Our estimation of the Hurst exponent for the CET ranging between 0.72 and 0.80 supports the LTP hypothesis. This is not just a simple statistical question since LTP would imply that long-lasting departures from the norm, cycles and clustering of anomalies are not infrequent events but the norm, and would make the identification of long-term trends more stringent.

Acknowledgements

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Supplementary Material

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