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How Extreme Were Daily Global Temperatures in 2023 and Early 2024?

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Key Points:

- At the current rate of global warming, a normal year 2023 would have equaled the record of 2016, without any help of El Niño
- The most extreme anomalies of 2023/24 rank among the most extreme of the entire record since 1940
- The 2023/24 heat can be reconciled with current estimates of global warming and an extreme but not implausible peak of internal variability

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Global temperatures were exceptionally high in 2023/24. Every month from June 2023 to June 2024 set a new record, and September shattered the previous record by 0.5°C. The 2023 annual average approached 1.5°C above pre-industrial levels. This results from both long-term warming and internal variability, with the occurrence of an El Niño episode. However the amplitude of the 2023/24 anomalies was remarkable and surprised the scientific community. Here we analyze the rarity of 2023/24 global temperatures from a climate perspective. We show that a ‘normal’ year 2023 would have roughly equaled the previous annual record, and that the most extreme events of 2023/24 rank among the most extreme since 1940. Our analysis suggests that the 2023/24 event can be reconciled with the long-term trend and an intense, but not implausible, peak of internal variability.

Plain Language Summary 2023 was the warmest year on record at global scale, and early 2024 has continued to break records. This remarkable episode has received a great deal of attention from the general public and the scientific community. It is well established that it is linked to the long-term global warming and the occurrence of an El Niño episode, but some temperature anomalies appeared so high, shattering previous records, that several scientists suggested that global warming may have been underestimated, which would have serious implications for future projections. Here we take a step back from the 2023/24 event, precisely quantify its rarity and compare it with other hot years. Using climate monitoring and extreme event attribution methods, we first show that at the current rate of warming, a ‘normal’ year 2023 would have equaled the ‘old’ record of 2016, even without any help of El Niño. We also find that the most extreme events of 2023/24 are among the most extreme of the entire record, but remain comparable with some past events. Our analysis thus suggests that the 2023/24 event is extreme but not incompatible with current estimates of global warming.

1. Introduction

The year 2023 has been the warmest year ever recorded globally (<https://wmo.int/publication-series/state-of-global-climate-2023>). Reference datasets report a annual anomaly of respectively 1.54 (BEST, <https://berkeleyearth.org/global-temperature-report-for-2023/>), 1.48 (ERA5, <https://climate.copernicus.eu/copernicus-2023-hottest-year-record>) and 1.46°C (HadCRUT5, <https://www.metoffice.gov.uk/hadobs/hadcrut5/>) relative to the 1850–1900 average, and of about 0.6°C relative to 1991–2020. All individual months from June–December 2023 have broken previous monthly records. These abnormally warm conditions continued into the first half of 2024, with all the monthly records for January to June also being broken (<https://climate.copernicus.eu/copernicus-june-2024-marks-12th-month-global-temperature-reaching-15degc-above-pre-industrial>). Forecasts suggest that this global heat episode is now waning, with a gradual return to normal levels in the second half of 2024 (Dunstone et al., 2024).

There are two main reasons for such a global heat. The first reason is that the Earth surface is currently warming due to external forcings. The global warming attributable to anthropogenic forcings is estimated to be 1.31 [1.1 – 1.7]°C in 2023 relative to 1850–1900, while natural forcings have a minor contribution (about 0.04°C, Forster et al. (2024)). A positive trend in a time series increases the rate at which high records are broken, and the greater the signal-to-noise ratio, the larger the rate (Wergen & Krug, 2010). For global temperature, the current signal (warming) is estimated to be 0.2°C per decade (Haustein et al., 2017; Ribes et al., 2021), which is relatively large compared to the noise: year-to-year variations have a standard deviation of about 0.1 to 0.2°C. It is therefore expected to regularly break temperature records, when conditions are ripe for a hot year.

This is precisely the second reason: internal climate variability — defined here as deviations of climate variables from their mean state due to internal processes — has provided favorable conditions to high surface temperatures

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in 2023/24. In particular it has been characterized by an El Niño episode that began in mid-2023 and lasted until mid-2024 (<https://wmo.int/news/media-centre/el-nino-forecast-swing-la-nina-later-year>). The El Niño Southern Oscillation (ENSO) is the first mode of interannual climate variability at global scale, with El Niño (La Niña) years hotter (colder) than the average. The El Niño event of 2023/24 was the strongest since 2015/16, and it followed several years spent in La Niña configuration (e.g., <https://www.mercator-ocean.eu/actualites/el-nino-update-november-2023/>). It has generated warm surface anomalies in the Tropical Pacific ocean, which have been compounded by other remarkable surface anomalies in other regions of the world. Indeed, the North Atlantic ocean had particularly high sea surface temperatures, and the Antarctic sea ice extent was record low (<https://wmo.int/publication-series/state-of-global-climate-2023>). Conditions were therefore ideal for 2023/24 to break global temperature records, as it was the case during recent major El Niño episodes (e.g., 1997/98 or 2015/16).

However the amplitude by which records were broken has been remarkable. The most striking example is the month of September 2023, with about 0.5°C above the previous record in 2020 (e.g., <https://climate.copernicus.eu/copernicus-september-2023-unprecedented-temperature-anomalies>). Some episodes lasting a few days also showed large anomalies and in mid-November the first day above 2°C warmer than pre-industrial was reported (<https://climate.copernicus.eu/global-temperature-exceeds-2degc-above-pre-industrial-average-17-november>). Such jumps in time series have drawn considerable attention. In particular, it has been shown that climate models hardly reproduce the margin by which the September record was broken (Rantanen & Laaksonen, 2024). This has led the scientific community to question whether this single episode of global heat provides evidence that global warming is currently underestimated (Schmidt, 2024).

Here we analyze global temperatures of 2023 and early 2024 using a climate monitoring approach. We use recently published statistical methods to (a) determine the non-stationary daily normals of global temperature, (b) assess the rarity of the 2023/24 anomalies and (c) contextualize this event by comparing it with previous episodes of global heat. An interactive application is supplied with the article to explore the results further (see Open Research Section).

2. Data and Methods

2.1. Data

The daily global temperature series used in this article is calculated as the global average of daily mean 2 m-temperatures provided by the ERA5 reanalysis and covering the period 1940–present (Hersbach et al., 2020). At the time of writing, we have data up to 30 June 2024, which is sufficient to cover the full global heat episode analyzed. For the calculation of non-stationary normals, we need an a priori estimate of the annual forced response of the global temperature (noted g_0 below). For this we use the estimate provided in Ribes et al. (2021) and recently updated (Forster et al., 2023, 2024). It results from a combination of past observations (HadCRUT5) and model simulations (CMIP6) via the KCC constraint method (Qasmi & Ribes, 2022). Model simulations have observed forcings until 2014, and follow an intermediate emission scenario (SSP2-4.5) afterward. The latter can be considered as a conservative assumption since it does not include recent positive forcings such as the reduction in man-made aerosols associated with marine shipping (<https://atmosphere.copernicus.eu/aerosols-are-so2-emissions-reductions-contributing-global-warming>), the increase in stratospheric water vapor due to Hunga Tonga's eruption (Jenkins et al., 2023), or the higher-than-expected amplitude of the current solar cycle (<https://www.nesdis.noaa.gov/news/time-lapse-of-solar-cycle-25-displays-increasing-activity-the-sun>). The potential impact of these forcings on the global mean temperature is estimated to be of a few hundredths of a °C (Schmidt, 2024).

2.2. Non-Stationary Normals

We calculate non-stationary daily normals illustrated in Figure 1a using a slightly adapted version of the procedure proposed by Rigal et al. (2019). This consists in breaking down the temperature T of a given day d and year y into a sum of smooth functions representing the mean annual cycle over the period (f), the yearly forced response (g) multiplied by a distortion of the annual cycle (h), and the anomaly of the day relative to its (non-stationary) normal (the residual ε):

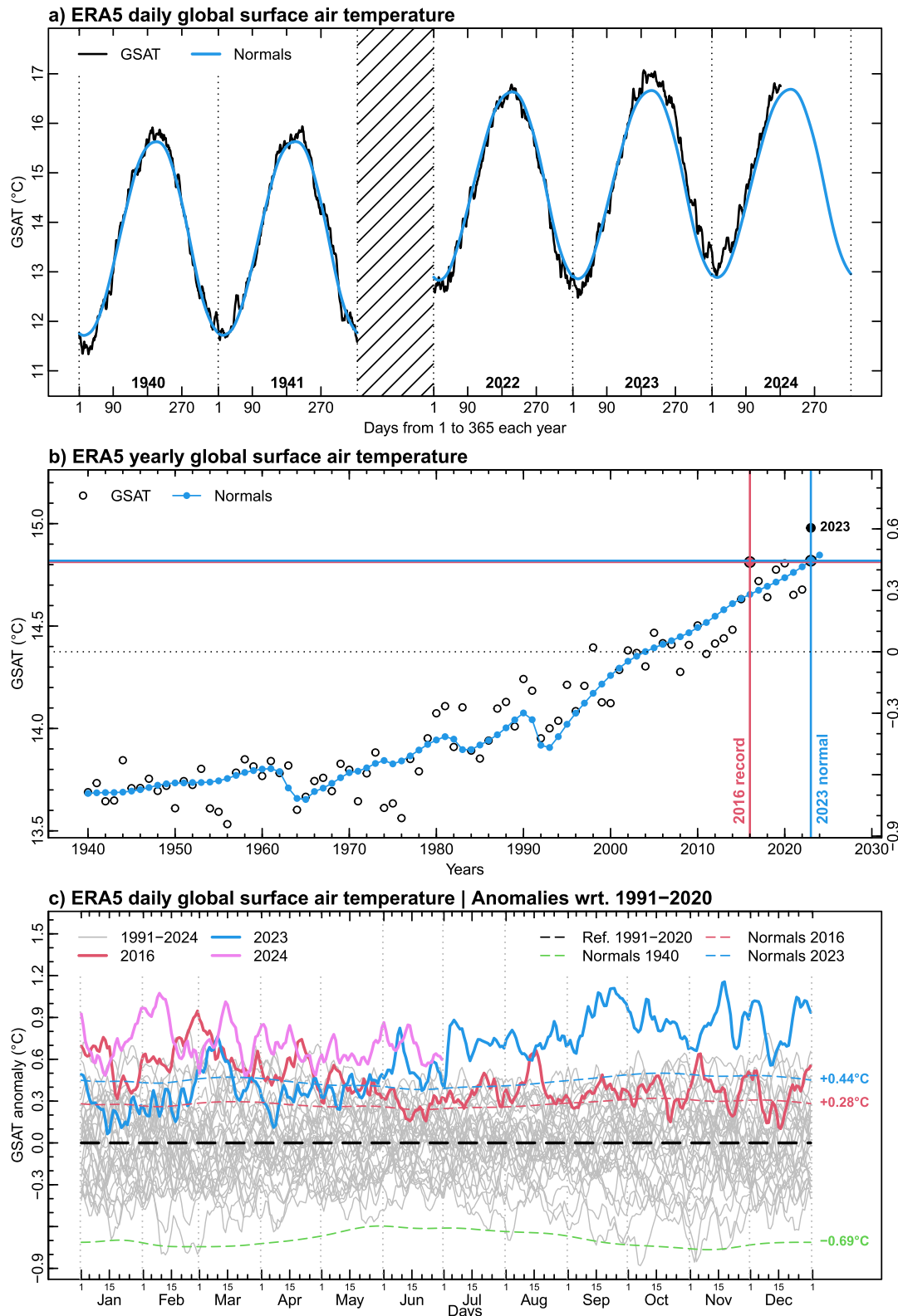


Figure 1. ERA5 global temperatures: the year 2023 and the non-stationary normals. (a) Daily temperatures (black line) and the estimated normal ($f + g \times h$, blue line). (b) Annual-mean temperatures (black dots) and the estimated normal (blue line), corresponding to the yearly forced response (g). Anomalies wrt. 1991–2020 are indicated on the right axis, 2016 and 2023 are highlighted. (c) Daily anomalies wrt. 1991–2020 for all years of 1991–2023 (solid lines), with 2016 and 2023 highlighted, and non-stationary daily normals of 1940, 2016 and 2023 (dashed lines), showing the distortion of the annual cycle (h), with annual means on the right.

$$T(d, y) = \underbrace{f(d) + g(y) \times h(d)}_{\text{non-stationary normal}} + \varepsilon(d, y). \quad (1)$$

We consider the time series of ERA5 daily global temperatures $T(d, y)$, with $d \in 1 : 365$ and $y \in 1940 : 2024$. We take a first estimate of the yearly forced component g over 1940–2024, which we denote g_0 , from an updated version of Ribes et al. (2021) (see Section 2.1). Then, for each day $i \in 1 : 365$, the corresponding 85 year time series $T_i = T(d = i, y)$ is linearly regressed onto g_0 so that $T_i = a_i + g_0 \times b_i$. The regression coefficients a_i and b_i (365 values each) are finally smoothed over days i from 1 to 365, using periodic smoothing splines. We choose 18 degrees of freedom for a_i and 9 for b_i , so that we capture variations at seasonal time scale while reducing sampling noise (Figure S1 in Supporting Information S1). The smoothed a_i directly provide the function $f(d)$ ($a_i = f(d = i)$), that is, the mean annual cycle of T . The smoothed b_i are normalized to equal one on average over the year, and then provide the function $h(d)$ ($b_i / \text{mean}(b) = h(d = i)$), that is, the distortion of the annual cycle with climate change. The normalization factor is reported on g_0 to provide the final estimate of the function g ($g_0 \times \text{mean}(b) = g$). This correction of the amplitude (not the shape) of the initial forced response is justified as we use ERA5 rather than HadCRUT5 in Ribes et al. (2021). In practice, we find $\text{mean}(b) = 1.022$, which is a slight upward revision of their estimate of forced warming.

2.3. Scanning Procedure

In Section 3.2, we use an automatic ‘scanning’ procedure that quantifies the rarity of observed anomalies over a wide variety of time windows of different dates and durations, and identifies the window that maximizes the rarity (Cattiaux & Ribes, 2018). This approach was initially proposed to help define a single weather event for climate monitoring or attribution purposes. It is applied here to the times series of daily global temperature anomalies, that is, the series $\varepsilon = T - (f + g \times h)$ (cf. Equation 1).

For each calendar window with a duration of 1, 3, 5, 7 ... 270, 300, 365 days (see y-axis values in Figures 2b and 2c), and centered on each day of the year (x-axis), we calculate the probability of having, in the climate of 2023/24, an anomaly equal to or greater than that observed in 2023/24. In event attribution studies, this is called the ‘factual’ probability, since it corresponds to the odds of the event occurring in the world as it is. It is noted p_1 and writes:

$$p_1 = \Pr\{X^{(t_1)} \geq x_{t_1}\}, \quad (2)$$

where $X^{(t_1)}$ is the random variable describing all possible realizations of the climate at time t_1 , and x_{t_1} is the value effectively observed at that time. p_1 has the statistical property of being uniformly distributed between 0 and 1, whatever the calendar window, which means that events of different dates and durations can be fairly compared. This probability can be conditioned (or not) by the time of the year, depending on whether we want to consider the event in its seasonal context. Here we explore both options, as we are interested in the rarity of both the amplitude and the timing of 2023/24 anomalies. Hence, we distinguish the *calendar* p_1 , that is, the probability that the event occurs at the same dates ± 15 days, and the *all-year* p_1 , that is, the probability that it occurs anytime in the year.

Both calendar and all-year p_1 are computed empirically. For a given time window $d1 : d2$ of duration n , we consider the corresponding mean anomaly effectively observed, $x = \text{mean}_{d1:d2}(\varepsilon)$. For the calendar p_1 , we compare x with the 85 year sample of n -day local maxima of ε within a calendar neighborhood $(d1 - 15) : (d2 + 15)$; we fit a normal distribution onto this sample and p_1 is given by the percentile level of x within this distribution. For the all-year p_1 , the calendar conditioning is removed, so the sample becomes the n -day annual maxima of ε . While it is common practice to use GEV distributions to fit annual-maxima of local or regional temperatures, here we also use normal distributions as they tend to have a higher goodness-of-fit than GEV distributions in this precise case (global temperature), especially for long durations (Figure S4 in Supporting Information S1). By construction, the all-year sample is thus made of values that are greater than in the calendar sample, hence the all-year p_1 is systematically greater than the calendar p_1 .

Finally, in Section 3.3, the search for the most extreme events is made as in Cattiaux et al. (2024). We extend the p_1 computation to the entire ERA5 time series of global temperatures, that is, (1940–2024). Then we search for local minima of p_1 in the date-duration diagrams (as in Figures 2b and 2c but extended to all years). We first

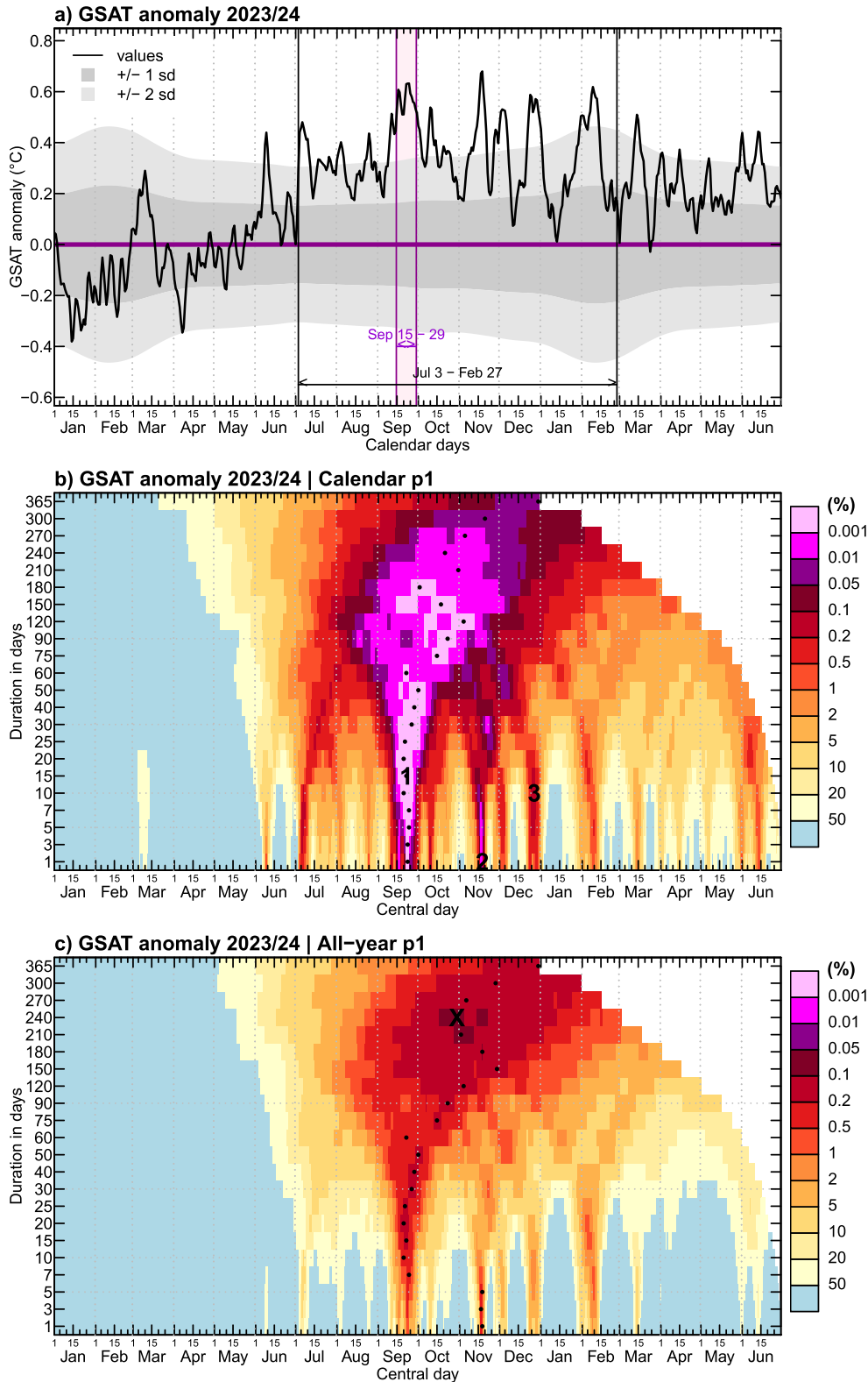


Figure 2. Analysis of the 2023 event. (a) ERA5 daily anomalies of global temperatures in 2023 wrt. Non-stationary normals (ϵ , black line), with shading for the ± 1 and 2 s.d. Levels. Associated (b) calendar and (c) all-year p_1 as a function of the time of the year (x-axis) and the temporal aggregation (y-axis). Minimum values for each duration are indicated (dots). The 3 events highlighted (1–3) in panel b are listed in Table 1 (calendar p_1); the event highlighted (X) in panel c is listed in Table 2 (all-time p_1).

identify the overall minimum of p_1 (the most extreme event), then mask all overlapping time windows (we consider that it is the same event), and then iterate to rank the p_1 minima in ascending order.

3. Results

3.1. Non-Stationary Normals of Daily Global Temperatures

Figure 1a shows daily global temperatures and our estimate of the non-stationary normal (see Section 2.2 for details). The normal is dominated by the seasonal cycle that has an amplitude of around 4°C and peaks in boreal summer, due to hemispheric asymmetry in surface thermal inertia. This seasonal cycle gradually rises and distorts with global warming. We find that the yearly average of the 2023 normal is 0.44°C above the 1991–2020 mean reference level (Figure 1b), or 1.32°C relative to 1850–1900 (Copernicus uses a 0.88°C difference between both periods), which is fully consistent with Forster et al. (2023, 2024). Interestingly, we find that the 2023 normal equals the previous record set in 2016; we estimate that global temperatures have increased by about 0.16°C between 2016 and 2023 (i.e., at a rate of 0.024°C per year), and that the 2016 record was *only* 0.16°C above its normal. In other words, this suggests that 2023 had a 50% chance to break the previous annual record, independently of internal variability. This result is sensitive to the emissions scenario used to estimate the forced response after 2014; using a higher (lower) scenario slightly increases (decreases) the 2023 normal, and therefore places it slightly above (below) the 2016 record (Figures S2 and S3 in Supporting Information S1) (Recall that recent forcings may have increased the global mean temperature by a few hundredths of a °C compared to the SSP2-4.5 baseline.)

The distortion of the seasonal cycle of global temperatures is rather small, but visible in Figure 1c. The highest warming is found in mid-October (0.50°C in 2023 wrt. 1991–2020) and the smallest one in mid-June (0.38°C). Also shown are observed daily temperatures for all years since 1991. From June 2023 onwards, global temperatures navigated quite far above other years. However the estimated normal for 2023 was already quite high, notably above 2016 temperatures in the second half of the year, and even above some daily records in August, September and October. As this season has a rather strong warming (peak in mid-October) and rather low inter-annual variability compared to the rest of the year (shown after), its signal-to-noise ratio is favorable for breaking warm records more frequently.

The year 2023 sets a new record for average global temperature, at 0.60°C above the 1991–2020 baseline (Figure 1b). According to our estimate of the non-stationary normal, this represents an anomaly ε of 0.16°C in the climate of 2023. At the yearly time scale, this is the fifth largest deviation in the entire ERA5 time series, notably behind 1998 (0.22°C, first), 1983 (0.21°C, second) or 1995 (0.19°C, third), but ahead of 2016 (0.16°C, sixth). At the recent rate of warming (estimated at 0.024°C/year, see above), this anomaly would become the new normal by 2030, suggesting that the annual record is likely to be broken again soon.

2023 therefore ranks among years associated with strong El Niño events. Yet ENSO traditionally culminates during the boreal winter, and thus affects 2 years, usually with a greater impact on the global temperature of the second year. 1983, 1995, 1998, and 2016 are all ‘second years’ of El Niño, and 2023 is by far the most abnormally warm of ‘first years’. Beyond the annual average, the particularity of 2023 global temperatures therefore lies in the timing of the strongest anomalies, with peaks in the second half of the year, early in the ENSO season. The following section precisely assesses the extremeness of 2023/24 temperature anomalies at the sub-yearly (daily) time scale.

3.2. Extremeness of Daily Anomalies in 2023 and Early 2024

Figure 2a shows the anomaly of 2023/24 relative to their own normals, that is, the ε term in Equation 1. It illustrates that the beginning of the year 2023 was rather cold, with peaks close to -0.4°C in January and April, which corresponds to -2 standard deviations (s.d.) at this time of year. From June 2023 onwards, the anomaly is almost always positive, often exceeding 2 s.d., particularly in September and November. It should be noted that there is an annual cycle in the standard deviation of global temperature anomalies: it is maximum around February and minimum in June/July. This is consistent with the seasonality of ENSO's influence on global temperature.

Now we are interested in characterizing what has *really* been extreme in the daily global temperatures of 2023/24. We scan the entire year 2023 and early 2024 in search of the time window with the most extreme temperature anomalies, that is, with the smallest *calendar* and *all-time* probabilities of occurrence p_1 as defined in Section 2.3.

Table 1
The Most Extreme Events of Global Temperature Anomaly, Ranked by Calendar p_1 (Rightmost Column)

#	Year	Dates	Duration	ϵ (°C)	s.d.	p_1 (%)
1.	2023	Sep 15 - 29	15	0.57	3.9	0.026
2.	2023	Nov 18	1	0.68	3.8	0.1
3.	1945	Aug 19 - 28	10	0.52	3.5	0.14
4.	1998	Aug 4 - 10	7	0.53	3.6	0.14
5.	1998	May 22 - Jun 20	30	0.43	3.3	0.15
6.	1995	Feb 7 - 13	7	0.69	3.1	0.41
7.	1998	Apr 4 - 8	5	0.54	3.2	0.48
8.	1997	Nov 5 - 9	5	0.53	3.2	0.5
9.	1987	Dec 11	1	0.62	3.3	0.52
10.	2023	Dec 23 - Jan 1	10	0.54	3.1	0.55

Note. The fifth and sixth columns indicate the anomaly in °C and s.d. at the exact dates. 2023–24 events are in bold.

The smallest calendar p_1 of 2023/24 is found for September 15 to 29, that is, a 15 day window (Figure 2b). The global temperature anomaly equals to 0.57°C on average over this window which corresponds to a 3.9 s.d. Departure from the normal at these exact dates. The calendar p_1 of 0.026% means that such a 15 day event had about a 1-in-4,000 chance of occurring at that time of the year (September 15 to 29 ± 15 days). After the September event, we find a second (local) minimum of p_1 for the 1 day event of November 18 (p_1 of 0.1%) — when Copernicus reported the first day above 2°C warmer than pre-industrial (<https://climate.copernicus.eu/global-temperature-exceeds-2degc-above-pre-industrial-average-17-november>) — and a third one for the 10 day event of December 23 to January 1 (p_1 of 0.55%). Minimizing p_1 across time windows means that any other definition of these events (e.g., a predefined month or season) would result in a less rare event.

If we remove the calendar conditioning, the probability of observing these events at any time of the year are greater, but remain small. For instance the September 15–29 event has an all-year p_1 of 0.8%, which can be interpreted as a formal return period of $1/p_1 \sim 120$ years for such a warmth (0.57°C) over any 15 day window. Across all time windows, the smallest all-year p_1 is found for a long 240 day event, roughly the 8 months from July 2023 to February

2024, which encompasses all the calendar events described above (Figure 2c). It equals to 0.4% and would thus correspond to a return period of 240 years. While these values are sensitive to methodological choices and should therefore be taken with caution (see the discussion in the next section), our results demonstrate the particularly extreme nature of the 2023/24 daily temperature anomalies. Finally, panels b and c show that the most extreme part of this episode has passed; anomalies since March 2024 are less pronounced, in line with the return to neutral ENSO conditions.

3.3. The 2023/24 Global Heat Among the Most Extreme on Record

We now extend the scanning procedure to the entire ERA5 time series of global temperatures, that is, (1940–2024). We use the same method as in Cattiaux et al. (2024) to compare the warm episodes of different years and establish a ranking of the most extreme events (see Section 2.3 for further details). The advantage of removing the non-stationary normals and working on the anomaly ϵ is to treat all years equally; we can therefore compare the rarity of two events from different years (and time windows) fairly.

Remarkably, the September and November 2023 episodes top the list of extreme warm weather events taken in their calendar context, and the December 2023 event also appears in the top 10 (calendar p_1 , Table 1). When the calendar conditioning is removed, the longer event of July 2023 to February 2024 ranks as the second most extreme on record (all-year p_1 , Table 2). Other events appearing in these rankings correspond to years marked by El Niño conditions, such as 1982/83, 1994/95, 1997/98 or 2015/16; Figures S5 and S6 in Supporting Information S1 show the p_1 date-duration diagram for 1997/98 and 2015/16, and more can be visualized on the interactive application (see Open Research Section). The scanning procedure based on the all-year p_1 tends to select events that are longer (e.g., 1997/98 and 2023/24 considered as a 200⁺-day events rather than several shorter ones) and closer to the climatological maximum of the standard deviation of global temperature (e.g., February 1995 or 2016).

Our results suggest that 2023/24 is relatively comparable to 1997/98 in terms of rarity, duration and temporal succession of warm peaks, but singular in its timing, with the most extreme events in September and November. We find a slightly greater rarity for 2023/24 than for 1997/98, but it is important to note that p_1 values reported in Tables 1 and 2 are sensitive to methodological choices. First, they depend on the calculation of the non-stationary normal over the entire period. For extreme events, p_1 values are inherently small and can be significantly affected by only a tiny difference in the normal. For instance, we calculated that a 0.03°C warmer normal in 2023/24 — which is consistent with estimates of recent forcings versus the SSP2-4.5 baseline — would make the July–February event three times less rare (all-time p_1 of 1.2%), and rank it third, behind that of 1998.

Second, the rankings of Tables 1 and 2 also slightly depend on the procedure used to estimate p_1 , in particular on the statistical distribution used to fit the data. We tested several choices and noticed that the top-10 events are

Table 2
Same as Table 1, but Ranked by All-Year p_1 (Rightmost Column)

#	Year	Dates	Duration	ϵ (°C)	s.d.	p_1 (%)
1.	1995	Feb 7 - 13	7	0.69	3.1	0.24
2.	2023	Jul 3 - Feb 27	240	0.35	3.1	0.41
3.	1998	Jan 28 - Aug 25	210	0.33	2.8	0.99
4.	2016	Feb 17 - Mar 8	20	0.52	2.7	1.4
5.	1958	Jan 25	1	0.65	3	2
6.	1983	Dec 16 - Mar 15	90	0.35	2.3	2.7
7.	1990	Mar 1 - 20	20	0.47	2.6	3.2
8.	1987	Dec 11	1	0.62	3.3	3.6
9.	1945	Aug 16 - 30	15	0.48	3.4	4.3
10.	1997	Nov 5 - 9	5	0.53	3.2	6.4

Note. The fifth and sixth columns still indicate the anomaly in °C and s.d. at the exact dates. 2023–24 events are in bold.

almost systematically the same, though sometimes in a different order (e.g., Table S1 in Supporting Information S1 for rankings of all-year p_1 with GEV distributions, and further tests available on the interactive application, see Open Research Section). In the end, although caution is needed with Tables 1 and 2, we are fairly confident that the global heat episodes in 2023/24 are among the most extreme in the entire series of ERA5 daily global temperatures.

4. Discussion and Conclusions

Our aim here was to assess how extreme the global temperatures of 2023 and early 2024 had been. We have first provided an estimate of daily non-stationary normals for global temperature to determine the level we could objectively expect in 2023/24, and showed that it was *as likely as not* that 2023 would break the annual record set in 2016, and even some of the daily records. Then we have examined the rarity of daily anomalies, and found that the global heat from July 2023 to February 2024 ranks among the most extreme of the entire global temperature series since 1940, and that in their calendar context, the September and November peaks are the most extreme ever on record.

Our analysis demonstrate that in a warming climate, the use of non-stationary normals is more relevant than a reference (fixed) climatology to comment on the rarity of hot anomalies. This particularly applies to global temperature, which has a high signal-to-noise ratio, since a record-high event quickly becomes the new normal. Further, our exhaustive scanning procedure enables us to step back from the 2023/24 episodes, and compare them with events from other years, calendar dates or durations on an equitable basis. Our results thus provide a particularly helpful insight on how to put global temperatures of 2023/24 into the perspective of climate change.

We conclude that having broken records in 2023/24 is no surprise given the current rate of warming. We can even expect some of the records set in 2023 and early 2024 to be quickly broken again. Yet 2023/24 is singular in the timing of the warmest anomalies, with the September and November peaks particularly extreme for this time of year. It is legitimate that they have surprised the community, and that the question of a possible underestimation of the global warming (forced response) has arisen (Schmidt, 2024). Here we find that the return period of the July 2023 to February 2024 heat episode is indeed high, but only slightly above some past events, in particular the 1997/98 El Niño episode. Importantly, we use a conservative assumption about the forced response in the latest years, and considering some recent forcings could even revise the rarity of 2023/24 downwards.

Taking a broad historical perspective thus tempers the unprecedented nature of the 2023/24 event. Our analysis suggests that we can reconcile this episode with the long-term trend and an intense, but not implausible, peak of internal variability (such as that of 1997/98). On the basis of this single event, evidence therefore remains limited to conclude whether global warming is underestimated or not in the current literature. It is essential to continue closely monitoring global temperatures in the upcoming months and years; the tools used here are perfectly relevant for this purpose.

Data Availability Statement

Input data and scanning results are available on a Zenodo archive (Cattiaux, 2024). This includes the global average of ERA5 daily temperatures (downloaded from Hersbach et al. (2023), last update: 30 June 2024), the initial estimate of the forced response g_0 , and the date versus duration matrices of estimated calendar and all-time p_1 . R scripts for computing the non-stationary normals, the scanning procedure and visualizing the results are available on GitHub: <https://github.com/jlnctx/CRC24/>. Additionally, an interactive R shiny application has been deployed to reproduce the Figures and Tables of the paper for all years and various methodological choices, and to further explore the results: <https://jlnctx.shinyapps.io/CRC24-app/>.

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