Actuarial Weather Extremes Series: Five Consecutive Months of Record-High Global Temperatures

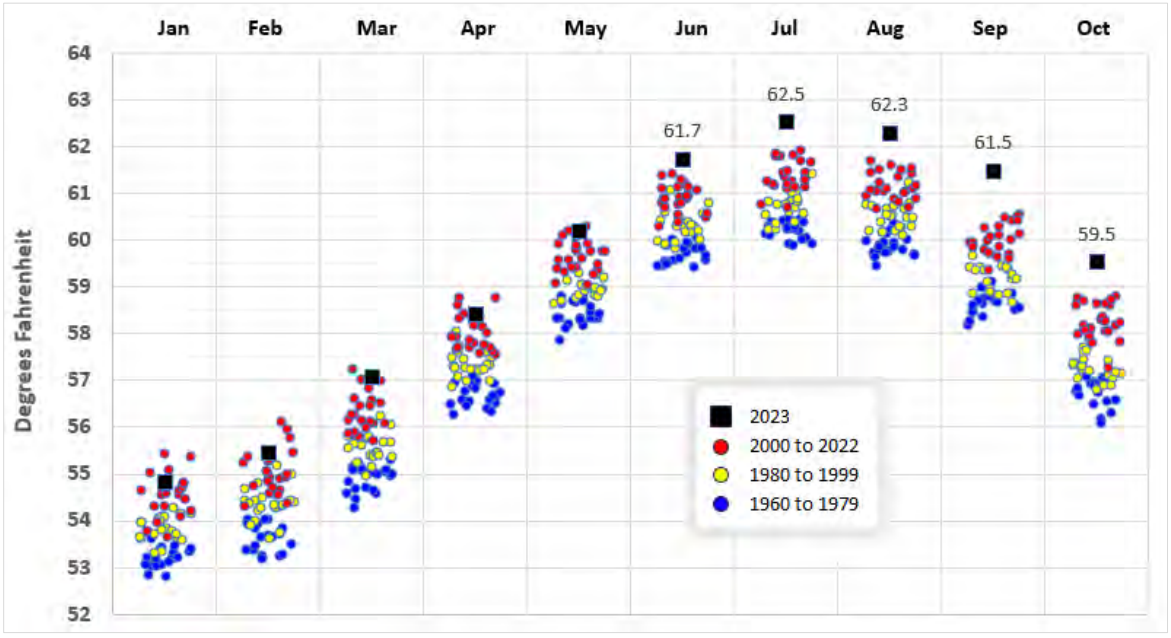
Patrick Wiese, ASA

November 2023

Five Consecutive Months of Record-High Global Average Temperatures

According to data produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), the average worldwide temperature exceeded the prior record-high for each of the last five months, from June 2023 through October 2023.

Figure 1
GLOBAL AVERAGE AIR TEMPERATURE BY MONTH: 2023 COMPARED TO PRIOR YEARS



Data source: ERA5 dataset produced by ECMWF. ERA5 provides various measures of temperature. This figure uses air temperature measured at 2 meters above the surface of the earth. Each observation is the average temperature computed across all days of the month and all 24 hours of each day. Data for September and October 2023 is preliminary and could potentially be revised.

Figure 1 displays the global average air temperature (measured just above the earth's surface), computed separately by month. Each circle represents a prior month between 1960 and 2022, while black squares represent data for 2023. ERA5 data – produced by the European Centre for Medium-Range Weather Forecasts – was used for the analysis. ERA5 is gridded reanalysis data that provides worldwide weather observations every 0.25 degrees of latitude and longitude. To generate the results in Figure 1, ERA5's gridded air temperature observations were averaged across the entire surface of the earth, over both land and sea[1].

Table 1 repeats the results presented in Figure 1, but with additional numerical details. Column 4 shows the 2023 temperature "anomaly", defined as the 2023 monthly temperature (column 1) minus the corresponding average computed across the 1960 to 2019 period (column 3). Column 6 presents the "standardized anomaly", defined as the anomaly (column 4) divided by the standard deviation (column 5) computed from the 1960 to 2019 reference period. For example, for October of 2023, the standardized anomaly is 3.06 – that is, the global average temperature in October 2023 was 3.06 standard deviations above the October average for the 1960 to 2019 period[2].

Table 1

GLOBAL AVERAGE AIR TEMPERATURE (FAHRENHEIT) COMPUTED ACROSS EACH CALENDAR MONTH

	1	2	3	4	5	6
	2023 Temp. (F)	Record High (F) Prior to 2023	Average 1960 to 2019 (F)	2023 Minus 1960 to 2019 Avg (F)	Stdev 1960 to 2019 (F)	2023 Degrees Above Avg / Stdev
Jan	54.84	55.44	53.88	0.96	0.62	1.54
Feb	55.44	56.15	54.37	1.07	0.66	1.62
Mar	57.06	57.26	55.61	1.45	0.67	2.18
Apr	58.43	58.80	57.35	1.08	0.61	1.78
May	60.18	60.31	59.04	1.14	0.56	2.04
Jun	**61.73**	61.43	60.31	1.42	0.53	2.67
Jul	**62.52**	61.93	60.78	1.74	0.52	3.31
Aug	**62.28**	61.72	60.53	1.75	0.57	3.07
Sep	**61.48**	60.58	59.29	2.19	0.61	3.59
Oct	**59.53**	58.82	57.44	2.09	0.68	3.06

Data source: ERA5 dataset produced by ECMWF. Data for September and October 2023 is preliminary and could potentially be revised. Red font indicates a record-high temperature.

It is worthwhile to briefly explain the seasonal cycle of global average temperature that is exhibited in the first 3 columns of Table 1. This seasonality may seem counterintuitive given that, on a global level, the earth receives about the same total amount of solar energy per day throughout the year. When the northern hemisphere experiences fall and winter, the southern hemisphere experiences spring and summer, and vice versa. Less daylight in one hemisphere is counterbalanced by more daylight in the opposing hemisphere. This suggests that the global average temperature should remain roughly constant from one month to the next. However, the northern hemisphere contains over two-thirds of the earth's land mass, and, in general, land heats up more quickly than does water in response to a given influx of solar energy[3]. Consequently, global average temperature carries a strong signature of the northern hemisphere's seasonal temperature changes.

---

[1] ERA5 grid points are evenly spaced with respect to degrees latitude and longitude, but they are not evenly spaced when measured in miles or kilometers. As one approaches the poles, lines of longitude converge, reducing the distance between grid points. Consequently, an unweighted average across grid points would result in the overweighting of data near the north and south poles. The standard remedy used by climate scientists (and used in this report) is to weight each data point by the cosine of its latitude. At the equator, the resulting weight is 1.0; at 45 degrees north or south of the equator, the weight is 0.71; at 60 degrees north or south, the weight is 0.50, declining rapidly to zero as one approaches either pole. The weights vary inversely with the spatial density of the grid points, leading to the desired effect: a uniform weight assigned to each square mile of the earth's surface.

[2] In the absence of climate change, one might expect standardized anomalies to resemble a standard normal distribution. In such a distribution, the probability of an observation exceeding 1.0, 2.0, or 3.0 standard deviations is 15.9%, 2.3%, and 0.1%, respectively.

[3] It takes more energy to increase water's temperature than it does for most other substances. "Specific heat" is the amount of heat energy it takes to raise or lower the temperature of 1 gram of a substance by 1°Celsius. The specific heat of liquid water is 1 calorie per gram per 1 degree C (cal/g/°C), which is greater than that of dry soil. Consequently, water both absorbs and releases heat more slowly than does land.

The fact that land and water have different warming rates in response to a unit of solar energy leads to the following questions: (1) are the record-high global average air temperatures in 2023 driven predominantly by high temperatures over the earth's land areas, and (2) is the average temperature of the world's oceans also at record-high levels, in parallel with record-high air temperatures? Table 2 provides data that can help answer these questions. The table presents four different temperature metrics, each computed using ERA5 data:

1. Global average air temperature computed across the entirety of the earth's surface. This is the same data presented in Figure 1 and Table 1.
2. Global average air temperature computed solely across the earth's land areas. Areas over water are excluded.
3. Global average air temperature computed solely across the areas above the earth's oceans and lakes.
4. Global average sea surface temperature. This is the temperature of water, as opposed to the temperature of air.

Table 2

GLOBAL AVERAGE TEMPERATURE (F) COMPUTED ACROSS EACH CALENDAR MONTH

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
1. Temperature in 2023 (F)										
Air temperature, entire earth	54.84	55.44	57.06	58.43	60.18	61.73	62.52	62.28	61.48	59.53
Air temperature, over land	38.12	39.80	44.68	48.83	53.90	58.52	60.61	59.86	57.40	51.88
Air temperature, over oceans	61.62	61.79	62.08	62.32	62.73	63.02	63.29	63.26	63.13	62.64
Sea surface temperature	65.19	65.47	65.68	65.67	65.51	65.63	65.90	66.15	65.97	65.62
2. Temperature in 2023 (F) minus the Historical Monthly Average (from 1960 to 2019)										
Air temperature, entire earth	0.96	1.07	1.45	1.08	1.14	1.42	1.74	1.75	2.19	2.09
Air temperature, over land	1.27	1.73	2.63	1.27	1.27	1.90	2.33	2.49	3.51	3.14
Air temperature, over oceans	0.83	0.81	0.97	1.00	1.09	1.22	1.49	1.45	1.65	1.67
Sea surface temperature	0.59	0.60	0.78	0.84	0.86	1.06	1.18	1.29	1.28	1.27
3. Temperature in 2023 (F) minus the Historical Average (from 1960 to 2019), Divided by the Historical Standard Deviation										
Air temperature, entire earth	1.54	1.62	2.18	1.78	2.04	2.67	3.31	3.07	3.59	3.06
Air temperature, over land	1.16	1.38	2.19	1.28	1.34	2.11	2.73	2.64	3.57	2.90
Air temperature, over oceans	1.70	1.66	1.97	2.13	2.53	2.95	3.57	3.29	3.39	3.07
Sea surface temperature	1.86	1.92	2.27	2.79	2.67	3.06	3.33	3.51	3.44	3.46
4. Percentile Ranking of 2023 Temperature Relative to Historical Data from 1960 through 2022										
Air temperature, entire earth	90.4%	93.6%	98.4%	93.6%	96.8%	100.0%	100.0%	100.0%	100.0%	100.0%
Air temperature, over land	84.1%	88.8%	98.4%	84.1%	79.3%	98.4%	100.0%	100.0%	100.0%	100.0%
Air temperature, over oceans	93.6%	90.4%	92.0%	95.2%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Sea surface temperature	92.0%	93.6%	96.8%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Data source: ERA5 dataset produced by ECMWF. Data for September and October 2023 is preliminary and could potentially be revised.

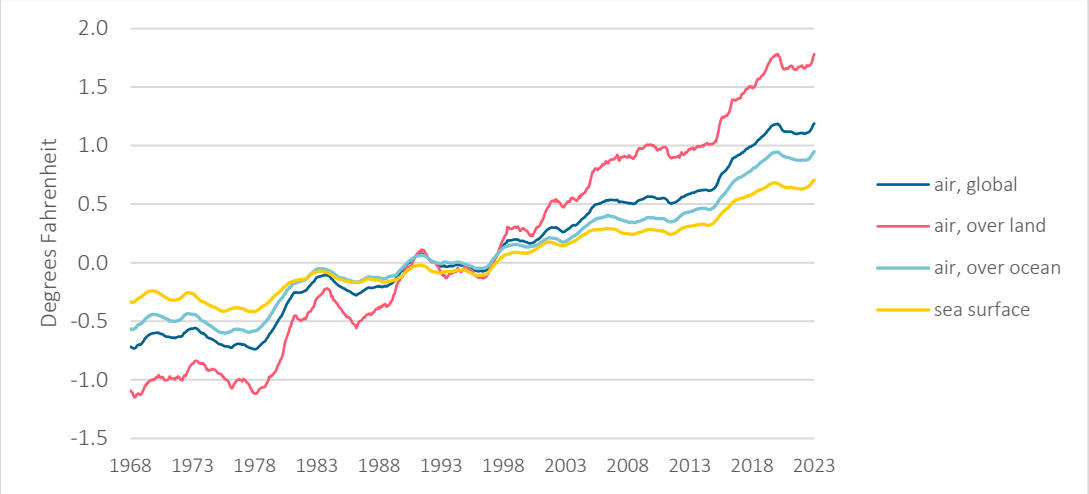
The table has 4 sections. Section 1 shows global temperature averages computed for each month of 2023; section 2 shows 2023 temperature anomalies computed by subtracting the corresponding historical monthly averages from the data in section 1; section 3 standardizes the anomalies by dividing them by the corresponding historical standard deviation, and section 4 shows the percentile rank of the 2023 data against the corresponding historical data. A ranking of 100% indicates a record-high temperature, while a ranking of 0% indicates a record-low temperature.

The results in section 4 reveal that global average sea surface temperature has been at record-high levels for 7 consecutive months, from April through October. Air temperature averaged across all areas covered by oceans has been at record-high levels for 6 consecutive months, and air temperature average across all land areas has been at record-high levels for 4 consecutive months. These record-high temperatures are well over 2 standard deviations above their historical averages, and more than 3 standard deviations for some months.

The temperature records of 2023 come on the heals of many decades of global warming. To provide a sense of historical warming trends, Figure 2 presents the 5-year trailing average[4] of monthly temperature anomalies, using the same definition of "anomaly" introduced previously (the temperature in a particular year and month, minus the historical 1960-2019 average for that month). In Figure 3, the anomalies are standardized by dividing by the corresponding historical standard deviations. Like Table 2, Figures 2 and 3 show 4 different temperature metrics: (1) air temperature averaged across the entire surface of the earth; (2) air temperature averaged across the earth's land areas; (3) air temperature averaged across those areas covered by water (i.e. oceans and lakes); and (4) average sea-surface temperature.

Figure 2

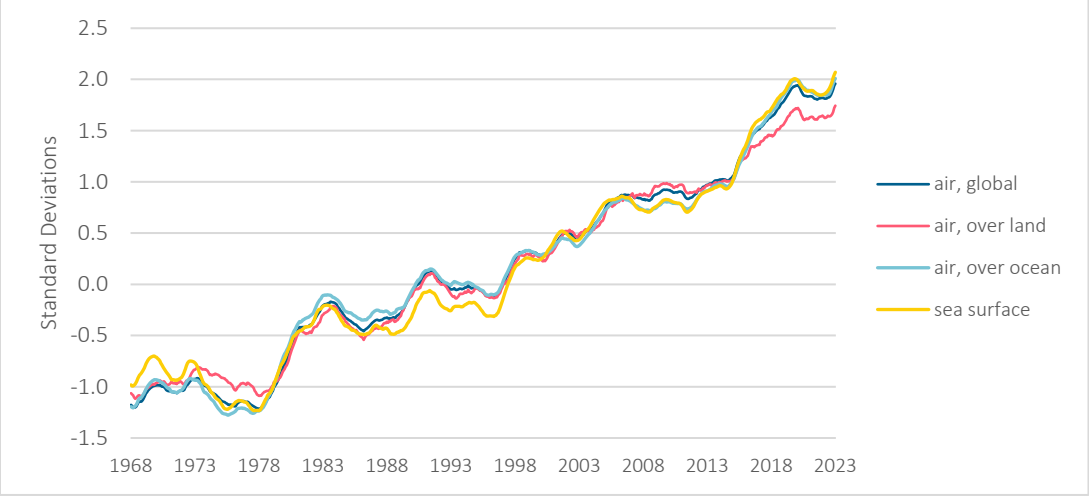
FIVE-YEAR TRAILING AVERAGE OF MONTHLY TEMPERATURE ANOMALIES (F)



Data source: ERA5 dataset produced by ECMWF.

Figure 3

FIVE-YEAR TRAILING AVERAGE OF STANDARDIZED MONTHLY TEMPERATURE ANOMALIES



Data source: ERA5 dataset produced by ECMWF.

[4] The 5-year trailing average temperature anomaly for October 2023 is equal to the average anomaly computed across the 60 months running from November 2018 through October 2023. Stepping back one month, the 5-year trailing average for September 2023 captures the 60 months running from October 2018 through September 2023.

Temperature Maps for Each Month in 2023

The analysis presented thus far in this report focuses on global average temperatures. The results summarize the macro-level state of planet, but provide no information about temperature in specific regions. Therefore, interactive Tableau maps were created to visualize temperature data for each ERA5 grid point. While ERA5 provides data every 0.25 degrees of latitude and longitude, the maps use data at one-degree intervals (i.e. integer values of latitude and longitude). This reduces the total amount of data and ensures that the maps' interactive features respond quickly to users' commands. The maps are available online:

https://tableau.soa.org/t/soa-public/views/GlobalTemperatureData2023/1Temperature

The upper lefthand corner of this Tableau visualization contains four tabs, providing access to four different color-coded maps of the temperature data. Each map has a toggle switch which facilities the selection any month from January 2023 through October 2023. Separately for each grid point, the four maps provide the following data:

1. The temperature in degrees Fahrenheit for the selected month (January 2023, February 2023, etc.).

2. The temperature anomaly (in degrees Fahrenheit) for the selected month. The anomaly is defined as the 2023 temperature for a specific month minus the 1960-to-2019 average temperature for the same month.

3. Identical to map #2, except the temperature anomalies have been standardized by dividing by the corresponding historical standard deviation. Note that standard deviation is computed separately for each grid point and each calendar month.

4. The percentile ranking of the 2023 temperature for the selected month. A ranking of 100% means that the 2023 temperature was a record-high compared to 1960-to-2022 temperatures for the same month. Conversely, a ranking of 0% indicates a record-low temperature.

Figures 4 and 5 were generated with the percentile ranking map, using data for October 2023. Figure 4 shows the percentile ranking for all grid points for October 2023, while Figure 5 shows only those grid points with a ranking of 95% or greater.

Figure 4

PERCENT RANKINGS OF OCTOBER 2023 TEMPERATURE AGAINST PRIOR OCTOBERS FROM 1960 TO 2022

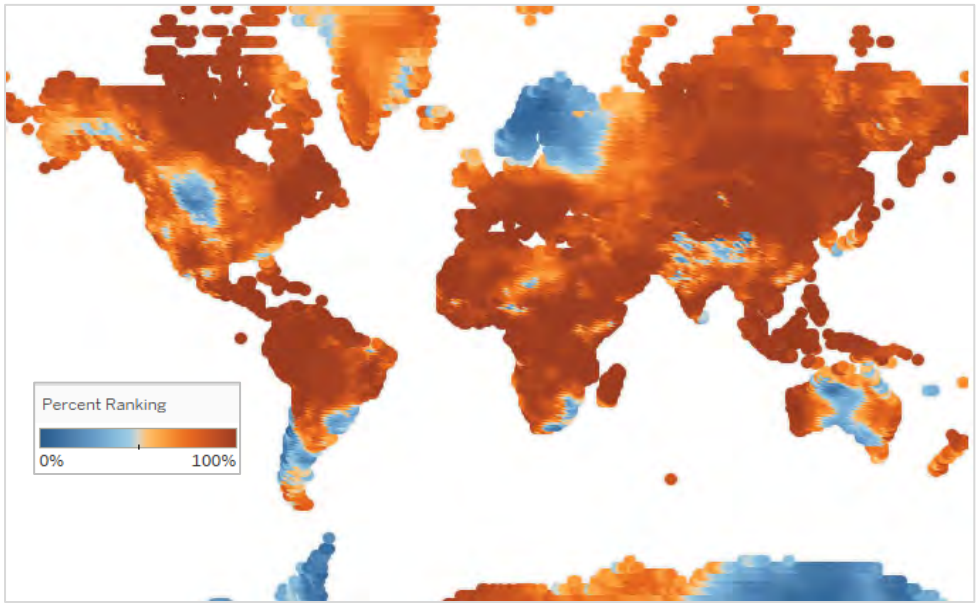


Figure 5
LOCATIONS FOR WHICH OCTOBER 2023 TEMPERATURE EXCEEDED THE 95TH HISTORICAL PERCENTILE

The figures reveal that large sections of Canada, Central and South America, Africa and Asia experienced near-record or record-high temperatures in October 2023. Note that the online maps facilitate the examination not only of data for October 2023, but also data for January through September 2023.

About The Society of Actuaries Research Institute

Serving as the research arm of the Society of Actuaries (SOA), the SOA Research Institute provides objective, data-driven research bringing together tried and true practices and future-focused approaches to address societal challenges and your business needs. The Institute provides trusted knowledge, extensive experience and new technologies to help effectively identify, predict and manage risks.

Representing the thousands of actuaries who help conduct critical research, the SOA Research Institute provides clarity and solutions on risks and societal challenges. The Institute connects actuaries, academics, employers, the insurance industry, regulators, research partners, foundations and research institutions, sponsors and non-governmental organizations, building an effective network which provides support, knowledge and expertise regarding the management of risk to benefit the industry and the public.

Managed by experienced actuaries and research experts from a broad range of industries, the SOA Research Institute creates, funds, develops and distributes research to elevate actuaries as leaders in measuring and managing risk. These efforts include studies, essay collections, webcasts, research papers, survey reports, and original research on topics impacting society.

Harnessing its peer-reviewed research, leading-edge technologies, new data tools and innovative practices, the Institute seeks to understand the underlying causes of risk and the possible outcomes. The Institute develops objective research spanning a variety of topics with its strategic research programs: aging and retirement; actuarial innovation and technology; mortality and longevity; diversity, equity and inclusion; health care cost trends; and catastrophe and climate risk. The Institute has a large volume of topical research available, including an expanding collection of international and market-specific research, experience studies, models and timely research.

Society of Actuaries Research Institute
475 N. Martingale Road, Suite 600
Schaumburg, Illinois 60173
www.SOA.org