Actuarial Weather Extremes Series: 2023 Was the Hottest Year on Record

Catastrophe and Climate

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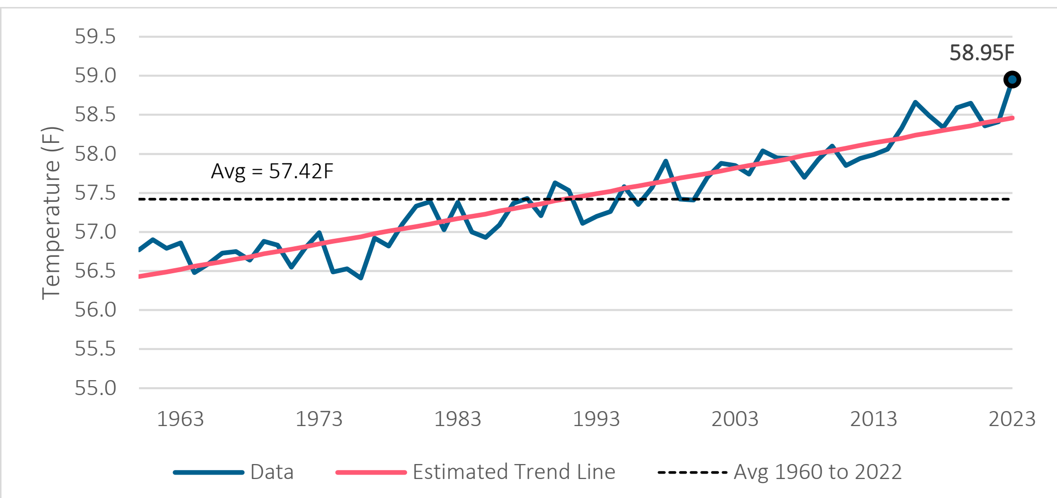
For the Earth as a Whole, 2023 Was the Hottest Year on Record

For the Earth as a whole, 2023 was the hottest on record according to data produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). Based on ECMWF data, the average worldwide air temperature[1] in 2023 was 58.95F, which is more than 1.5F above the historical average of 57.42F computed across the period from 1960 to 2022. The standard deviation of the time series of global average temperatures is 0.62F; therefore, a temperature anomaly of 1.5F is equivalent to about 2.5 standard deviations above the 1960-to-2022 average.

Figure 1

GLOBAL AVERAGE AIR TEMPERATURE (F) MEASURED TWO METERS ABOVE THE EARTH'S SURFACE



Data source: ERA5 monthly dataset produced by ECMWF. The data for November and December 2023 is preliminary and could potentially be revised.

[1] Please refer to the final section of this report for a description of the methodology used to calculate the worldwide average temperature.

The record global average air temperature in 2023 is attributable to record-high monthly temperatures from June through December, as illustrated in both Figure 2 and Table 1:

Figure 2

GLOBAL AVERAGE AIR TEMPERATURE (F), BY MONTH

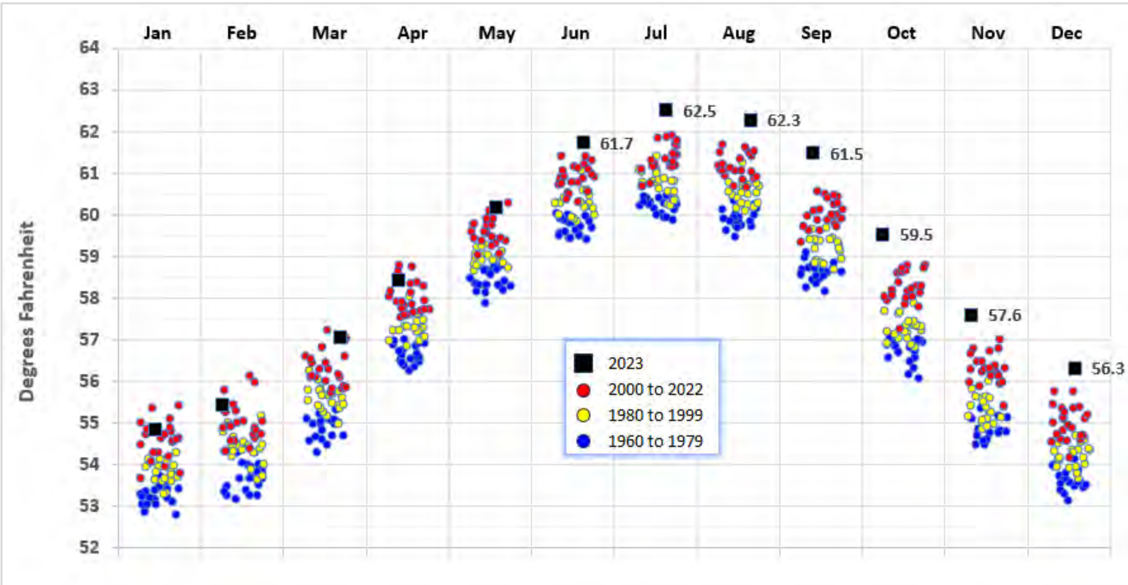


Table 1

GLOBAL AVERAGE AIR TEMPERATURE FOR EACH MONTH OF 2023, COMPARED AGAINST HISTORICAL DATA

1	2	3	4	5	6	7
Month	Temp (F) In 2023	Monthly Average Temp (F) 1960 to 022	Anomaly: 2023 Temp Minus Historical Average (F)	Historical Standard Deviation (F)	2023 Anomaly Divided by Standard Deviation	Percentile Ranking of 2023 Against 1960 to 2022
Jan	54.84	53.94	0.90	0.66	1.37	90.4%
Feb	55.44	54.42	1.02	0.69	1.47	93.6%
Mar	57.06	55.66	1.40	0.70	2.00	98.4%
Apr	58.43	57.40	1.03	0.64	1.61	93.6%
May	60.18	59.09	1.09	0.59	1.86	96.8%
Jun	61.73	60.35	1.38	0.56	2.44	100.0%
Jul	62.52	60.83	1.69	0.56	3.02	100.0%
Aug	62.28	60.57	1.71	0.60	2.86	100.0%
Sept	61.48	59.35	2.13	0.65	3.28	100.0%
Oct	59.53	57.50	2.03	0.72	2.82	100.0%
Nov	57.60	55.56	2.04	0.68	2.98	100.0%
Dec	56.32	54.36	1.96	0.65	3.02	100.0%

In Figure 2, each circle represents the average global air temperature in a prior month between 1960 and 2022, while black squares represent data for 2023. Table 1 provides greater detail for each month of 2023. Column 4 displays the monthly temperature "anomaly", equal to the difference between the temperature in 2023 and the historical average for the same calendar month. Column 6 presents standardized anomalies, computed as the anomaly in column 4 divided by the historical standard deviation shown in column 5. Lastly, column 7 shows the 2023 monthly temperature ranked against historical data from 1960 through 2022 for the corresponding calendar month. From June through December, the ranking of 100% indicates a record-high temperature; thus, 2023 concluded with seven consecutive months of record-high global average air temperatures.

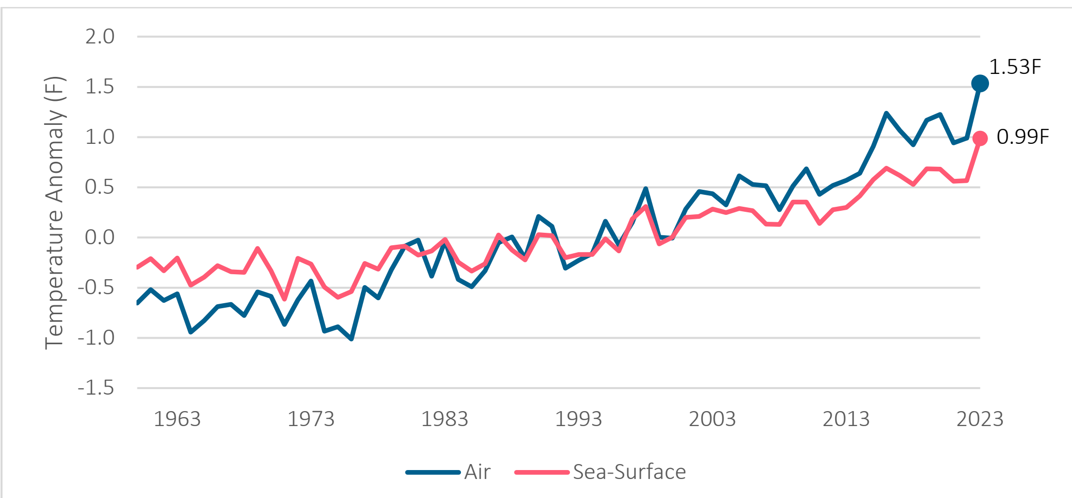
It is worthwhile to briefly explain the seasonal cycle of global average temperature that is apparent in Table 1 and Figure 2. This seasonality may seem counterintuitive given that, on a global level, the earth receives about the same total amount of solar energy per day throughout the year. When the 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[2]. Consequently, global average temperature carries a strong signature of the northern hemisphere's seasonal temperature changes.

Record-High Sea-Surface Temperatures

Record-high air temperatures in 2023 were accompanied by record-high sea-surface temperatures. As depicted in Figure 3, the global average sea-surface temperature (SST) in 2023 was 0.99F above its 1960-2022 average, exceeding the prior record SST anomaly of 0.69F set in 2016. Simultaneously, the global average air temperature anomaly in 2023 was at a record-high level of 1.53F, exceeding its prior record of 1.24F, also set in 2016.

Figure 3

GLOBAL AIR TEMPERATURE ANOMALIES VERSUS GLOBAL SEA-SURFACE TEMPERATURE ANOMALIES



Each anomaly is computed as the average temperature in a particular year minus the corresponding average across the period from 1960 through 2022. The anomalies are computed separately for air temperature and sea-surface temperature.

Table 2 presents monthly SST data, revealing record-high sea-surface temperatures for 9 consecutive months, from April through December of 2023.

[2] 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 (call/g/°C), which is greater than that of dry soil. Consequently, water both absorbs and releases heat more slowly than does land.

Table 2

GLOBAL AVERAGE SEA-SURFACE TEMPERATURE FOR 2023, COMPARED AGAINST HISTORICAL DATA

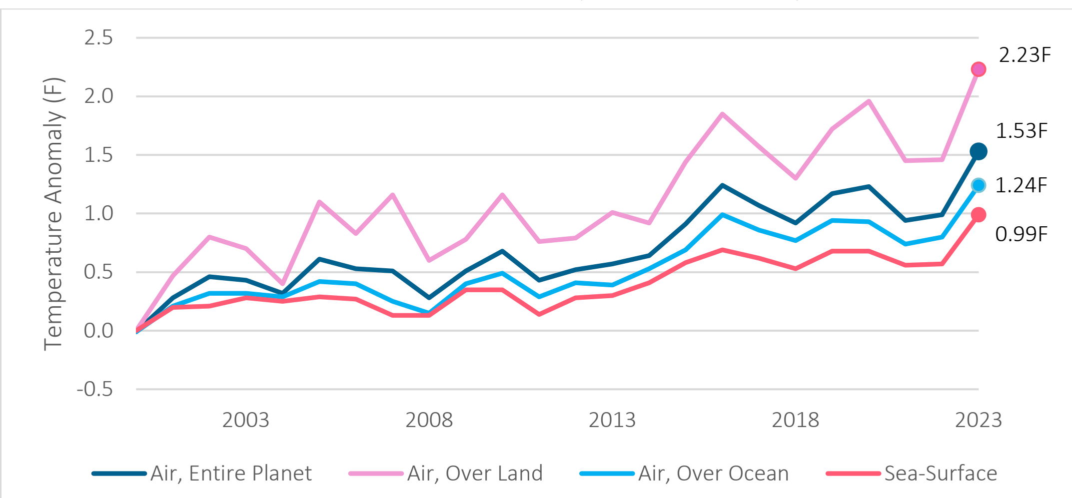
1	2	3	4	5	6	7
Month	Temp (F) In 2023	Monthly Average Temp (F) 1960 to 022	Anomaly: 2023 Temp Minus Historical Average (F)	Historical Standard Deviation (F)	2023 Anomaly Divided by Standard Deviation	Percentile Ranking of 2023 Against 1960 to 2022
Jan	65.19	64.63	0.56	0.34	1.65	92.0%
Feb	65.47	64.89	0.58	0.33	1.74	93.6%
Mar	65.68	64.93	0.75	0.36	2.07	96.8%
Apr	65.67	64.86	0.81	0.32	2.53	100.0%
May	65.51	64.67	0.84	0.34	2.46	100.0%
Jun	65.63	64.60	1.03	0.36	2.83	100.0%
Jul	65.90	64.76	1.14	0.37	3.06	100.0%
Aug	66.15	64.90	1.25	0.39	3.20	100.0%
Sept	65.97	64.73	1.24	0.39	3.16	100.0%
Oct	65.62	64.38	1.24	0.39	3.22	100.0%
Nov	65.42	64.22	1.20	0.36	3.32	100.0%
Dec	65.53	64.33	1.20	0.35	3.40	100.0%

Air Temperature Over Land versus Air Temperature Over the Oceans

Figure 3 reveals that average air temperature, computed across the entire surface of the earth, has risen at a faster rate in recent decades than has global average sea-surface temperature[3]. Given this finding, it is worthwhile to disaggregate the air temperature data into two components: (1) areas over land and (2) areas over oceans. Figure 4 presents over-land and over-ocean air temperature averages, along with the global average sea-surface temperature. To avoid cluttering the graph, only the period from 2000 onwards is plotted.

Figure 4

GLOBAL TEMPERTAURE ANOMALIES: AIR-OVER-LAND, AIR-OVER-OCEANS, AND SEA-SURFACE

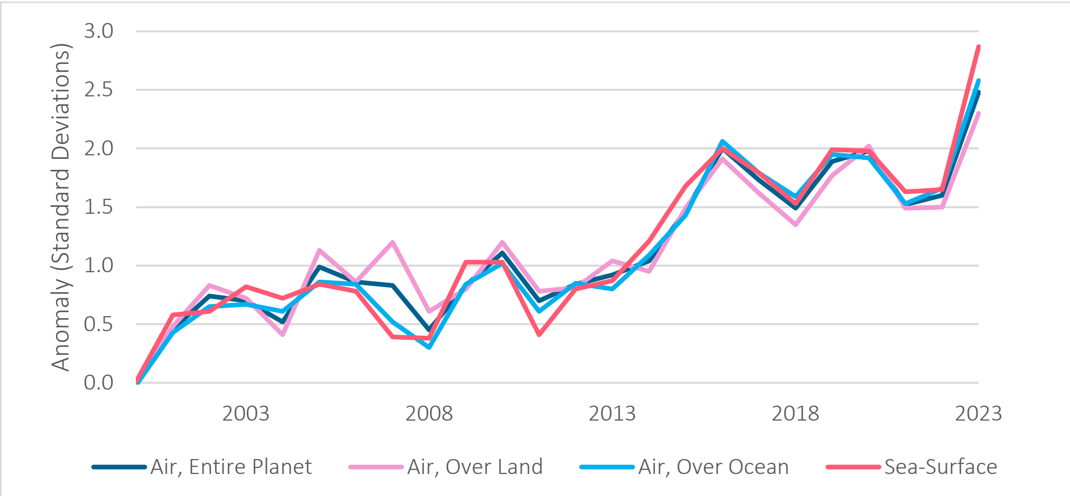


Each anomaly is computed as the average temperature in a particular year minus the corresponding average across the period from 1960 through 2022.

[3] For readers who would like to understand why land temperatures have risen faster than sea temperatures over recent decades, the following article provides an easy-to-understand explanation: https://www.weforum.org/agenda/2020/09/why-does-land-warm-faster-than-oceans/

Figure 4 reveals that the average air temperature over land has risen at a significantly faster rate compared to average air temperature over the oceans. In 2023, the average over-land air temperature was 2.23F above its 1960-to-2022 average, while the average over-ocean air temperature anomaly was 1.24F. Interestingly, if each of the time series in Figure 4 is divided by its respective historical standard deviation, the resulting "standardized anomalies" are quite similar across the four different temperature metrics, as illustrated in Figure 5.

Figure 5
STANDARDIZED TEMPERATURE ANOMALIES: AIR-OVER-LAND, AIR-OVER-OCEANS, AND SEA-SURFACE



Each standardized anomaly is calculated by dividing the anomaly (the average temperature in a particular year minus the corresponding average across the period from 1960 through 2022) by the historical standard deviation. In the absence of climate change, the probability of a standardized anomaly of 2.5 standard deviations or greater would be about 0.6%, and the probability of a series of consecutive large anomalies would be effectively zero.

Long-Term Warming Trends

Figures 1, 3, 4, and 5 reveal strong upward trends for both air temperature and sea-surface temperature. While global warming rates can change across time, it is nevertheless useful to fit a linear regression to the data (the time series of annual temperatures), thereby producing an estimated rate-of-warming that is constant across time. Table 3 presents regression results which include both the "best" estimate for the warming trend as well as the 95% confidence interval.

Table 3
ESTIMATED RATE OF WARMING (F) PER DECADE USING LINEAR REGRESSION FITTED TO 1960 TO 2023 DATA

Weather Data	Low End of 95% Confidence Interval	Best Estimate	High End of 95% Confidence Interval
Air Temperature, Entire Earth	0.292	0.323	0.354
Air Temperature, Over Land	0.451	0.501	0.551
Air Temperature, Over Oceans	0.225	0.251	0.276
Sea-Surface Temperature	0.152	0.174	0.196

For air temperature over land, the estimated warming rate is about a half a degree Fahrenheit per decade. The 95% confidence interval runs from 0.45 to 0.55 degrees Fahrenheit per decade. The estimated warming rate for air temperature over land is nearly twice the rate for air temperature over oceans, and nearly three times the rate for sea-surface temperature.

Interactive Temperature Maps Are Available Online

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, and are accessible online:

https://tableau.soa.org/t/soa-public/views/MapsofGlobalTemperatureData2023/1Temperature

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.

There are seven separate maps, each accessible via a clickable tab. Each map includes both air temperature and sea-surface data. Each map presents a different temperature-related metric, as follows:

- Map 1 displays the average temperature (in degrees Fahrenheit) across 2023, separately for each grid point.
- Map 2 displays the average temperature in 2023 for each grid point, minus the grid point's historical average temperature from 1960 through 2022. These temperature "deltas" or differences are referred to as "temperature anomalies".
- Map 3 displays each grid point's 2023 temperature anomaly, divided by the standard deviation of the grid point's time series of annual temperatures from 1960 through 2022. These metrics are referred to as "standardized anomalies". A value of 2.0, for example, indicates that the anomaly in 2023 was two standard deviations above its historical mean.
- Map 4 ranks each grid point's 2023 temperature against historical data from 1960 through 2022. A rank of 100% indicates a record-high temperature, a rank of 0% indicates a record-low, and a rank of "N" percent indicates that the 2023 observation falls at the n^{th} percentile of the historical distribution.
- Map 4b is similar to map 4, displaying percentile rankings of 2023 temperature against historical data from 1960 through 2022. However, map 4b uses a different color scheme that provides greater differentiation across the 90 to 100^{th} percentile range. Note that in map 4b, all percentiles below the 90th share the same color.
- Map 5 displays the standard deviation (in degrees Fahrenheit) of each grid point's annual temperature time series (from 1960 through 2022). These values are used to convert the anomalies into standardized anomalies.
- Map 6 displays the slope of a trendline fitted to the 1960 to 2023 time series of annual temperatures using linear regression. The slope is expressed as degrees Fahrenheit per decade. For example, a trend of 0.5 means that, for a particular grid point, the estimated warming trend is 0.5F per decade.

By default, each map displays data for the entire universe of grid points; however, a filter on the right-hand size of each map can be used to focus solely on the subset of grid points with data falling into any user-specified range.

Figures 6, 7, and 8 present standardized anomalies in 2023 (from map 3) for air-temperature data over land areas, air-temperature over oceans, and sea-surface temperature, respectively.

Figure 6

STANDARDIZED ANOMALIES FOR 2023: AIR TEMPERATURE OVER LAND

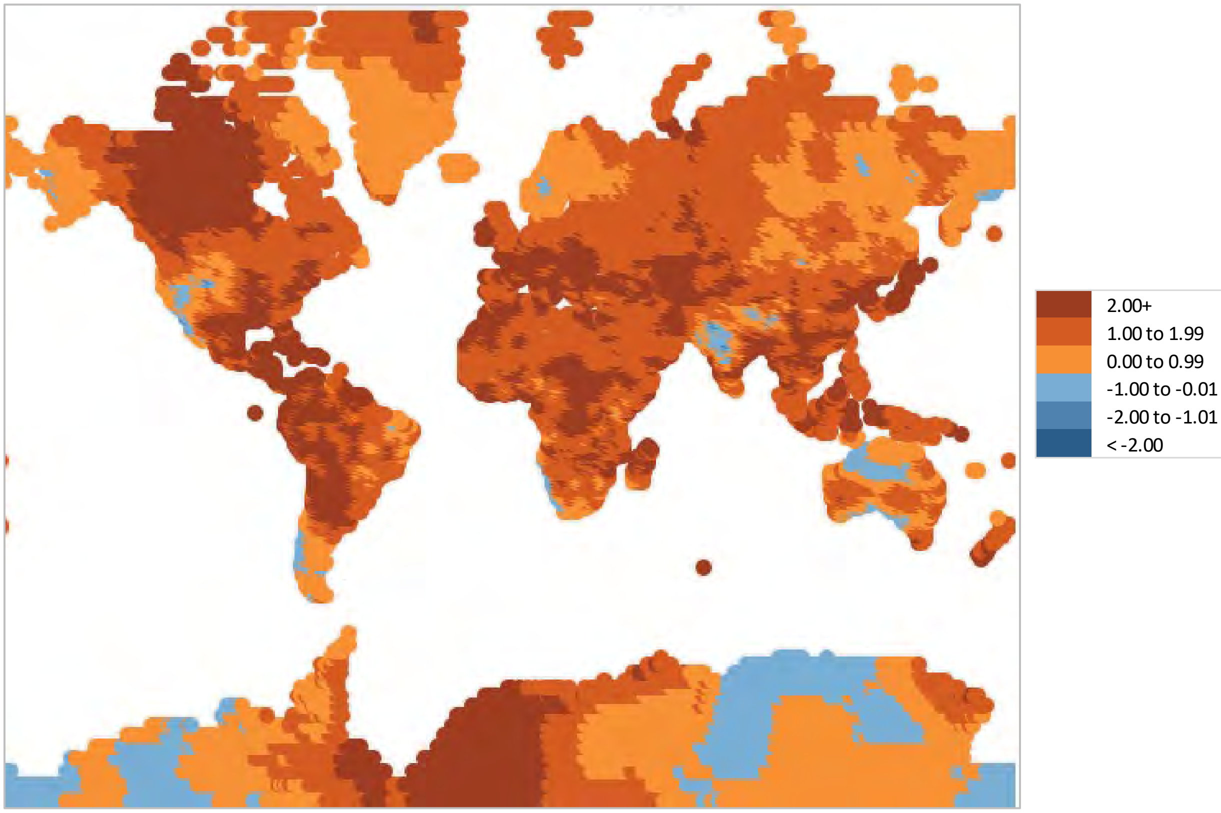


Figure 7

STANDARDIZED ANOMALIES FOR 2023: AIR TEMPERATURE OVER OCEANS

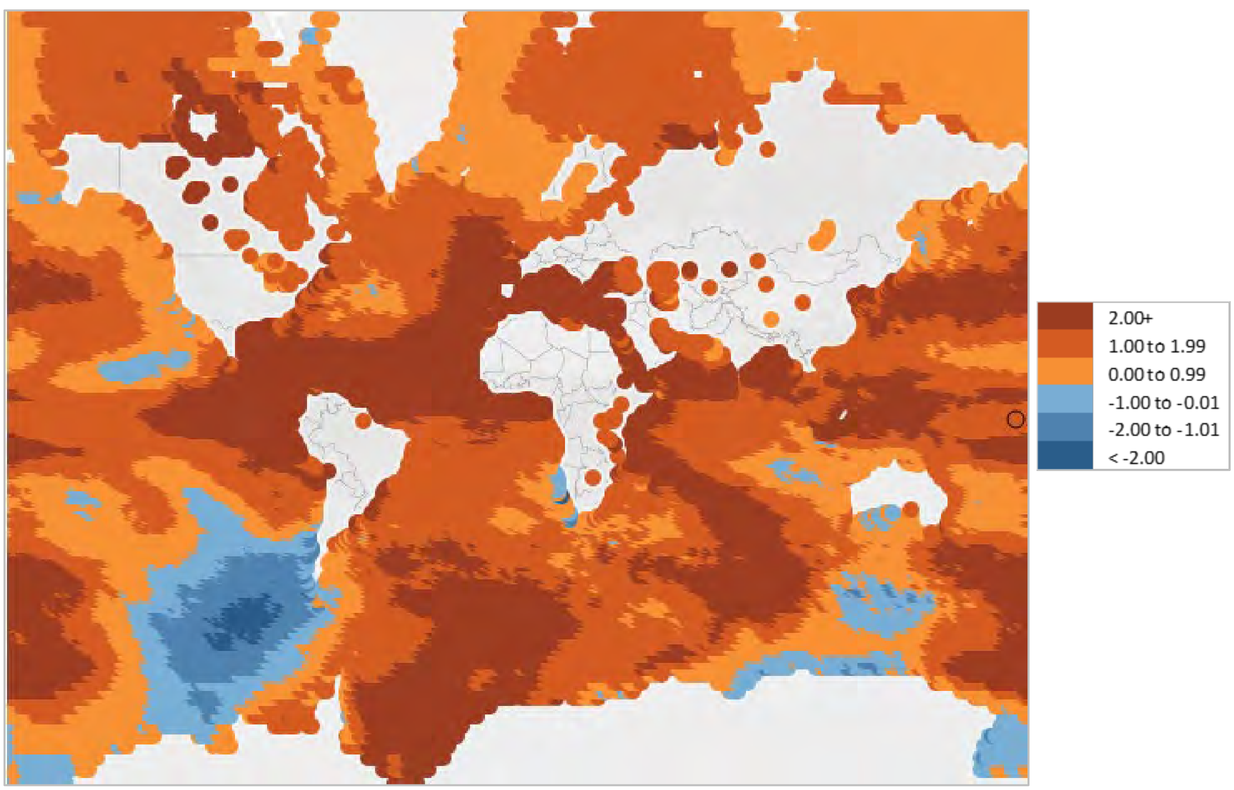
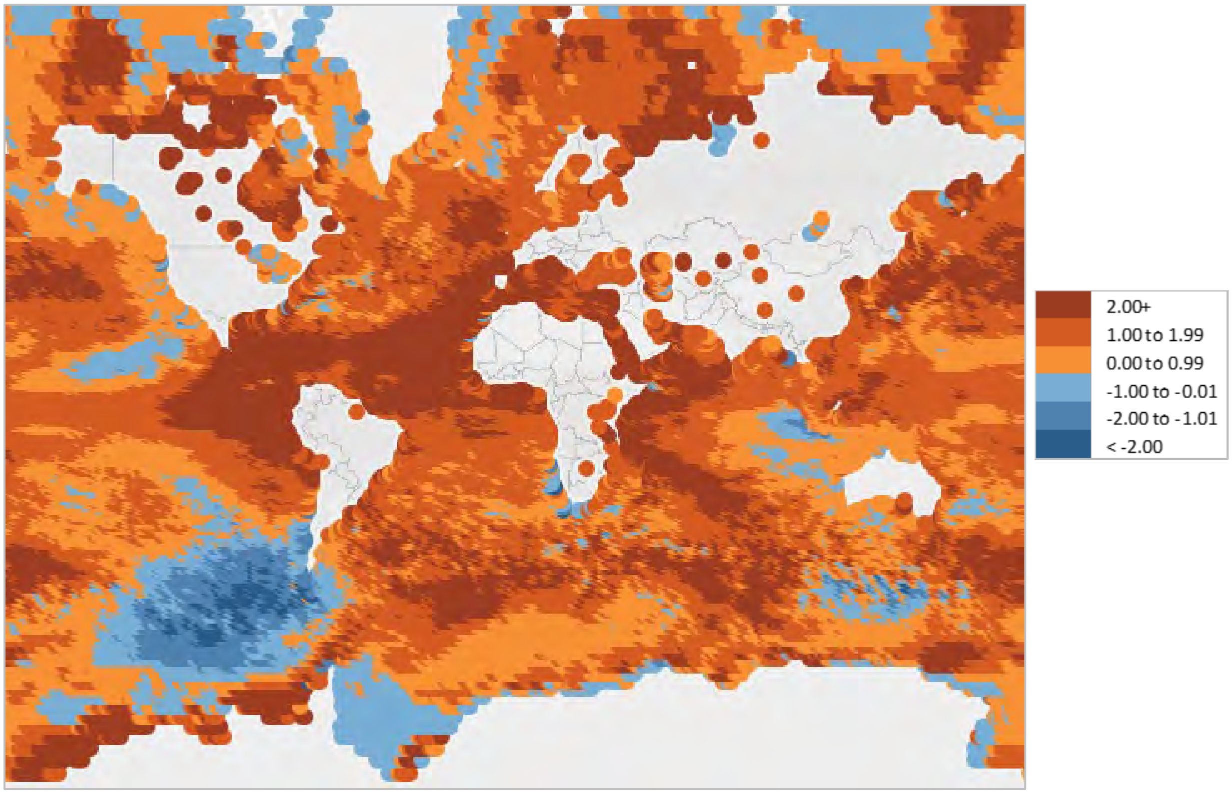


Figure 8

STANDARDIZED ANOMALIES FOR 2023: SEA-SURFACE TEMPERATURE



Figures 6, 7 and 8 reveal that, in 2023, most of the planet's surface experienced temperatures more than one standard deviation above historic, location-specific norms (based on 1960 to 2022 data), and anomalies greater than 2.0 standard deviations were quite common. Indeed, the fraction of the earth's surface with temperature anomalies exceeding 1.0 and 2.0 standard deviations was at a record-high level in 2023, as illustrated in Figures 9 and 10. This isn't surprising given that the earth's global average temperature – computed across its entire surface – reached a new peak in 2023, as presented earlier in Figures 1, 2 and 3.

Figure 9

PERCENT OF EARTH'S SURFACE IN 2023 WITH AVERAGE TEMPERATURE OVER ONE STANDARD DEVIATION ABOVE THE LOCATION-SPECIFIC 1960-TO-2022 AVERAGE

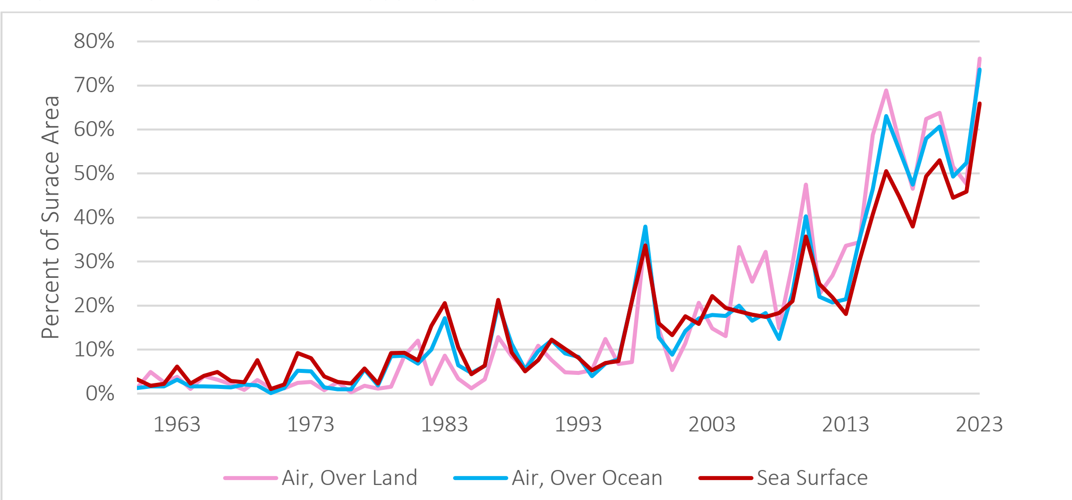
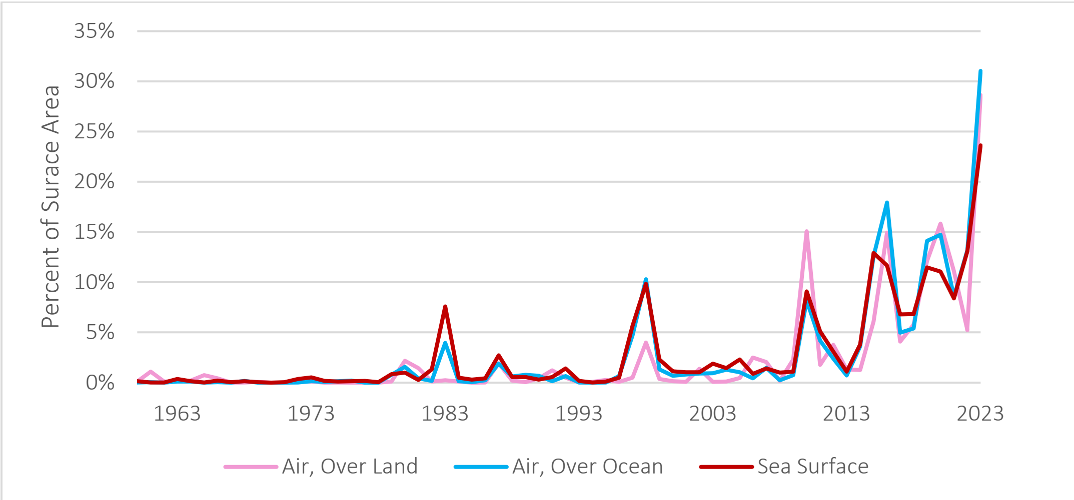


Figure 10

PERCENT OF EARTH’S SURFACE IN 2023 WITH AVERAGE TEMPERATURE OVER TWO STANDARD DEVIATIONS ABOVE THE LOCATION-SPECIFIC 1960-TO-2022 AVERAGE



Methodology for Computing the Worldwide Average Temperature

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 global 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 the approach used for the analysis presented 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, 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. This decline counterbalances the increasing density of grid points near the poles, resulting in an even spatial weighting across the surface of the earth.

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