Actuarial Weather Extremes Series: Quarterly Global Warming Report

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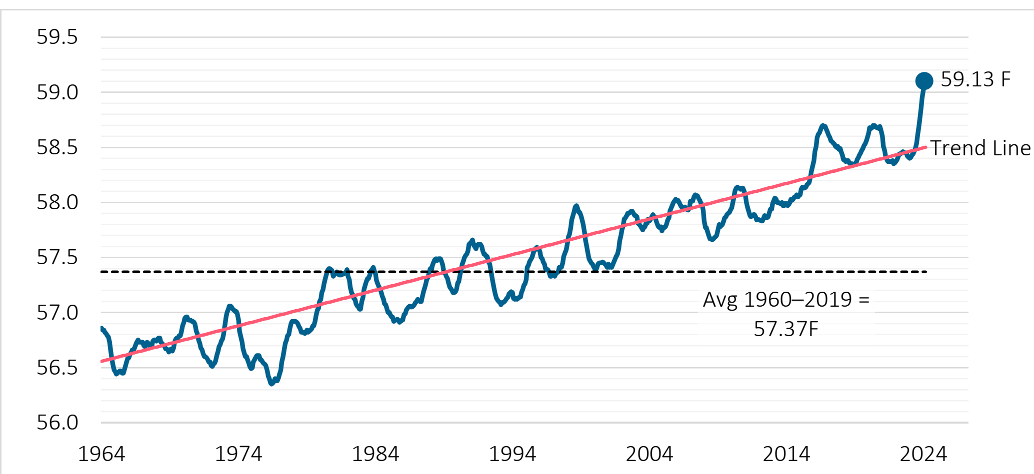
Global Warming Trends through March 2024

The Society of Actuaries Research Institute has, in recent years, issued several reports that provide a statistical summary of global warming trends. Because of the importance of this topic to the insurance industry and to society at large, these reports will now be issued quarterly. This report is the first of the quarterly series, reflecting temperature data through the end of March 2024. The data source for this report is ERA5, produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). As depicted in Figure 1, April 2023 to March 2024 is the warmest 12-month period on record for air temperature averaged across the entire surface of the earth. Across this period, the global average temperature was 59.13F, which is 1.76F above the long-term average of 57.37F computed across the 60 years from 1960 to 2019.

Figure 1

12-MONTH TRAILING AVERAGE OF GLOBAL AIR TEMPERATURE (F)



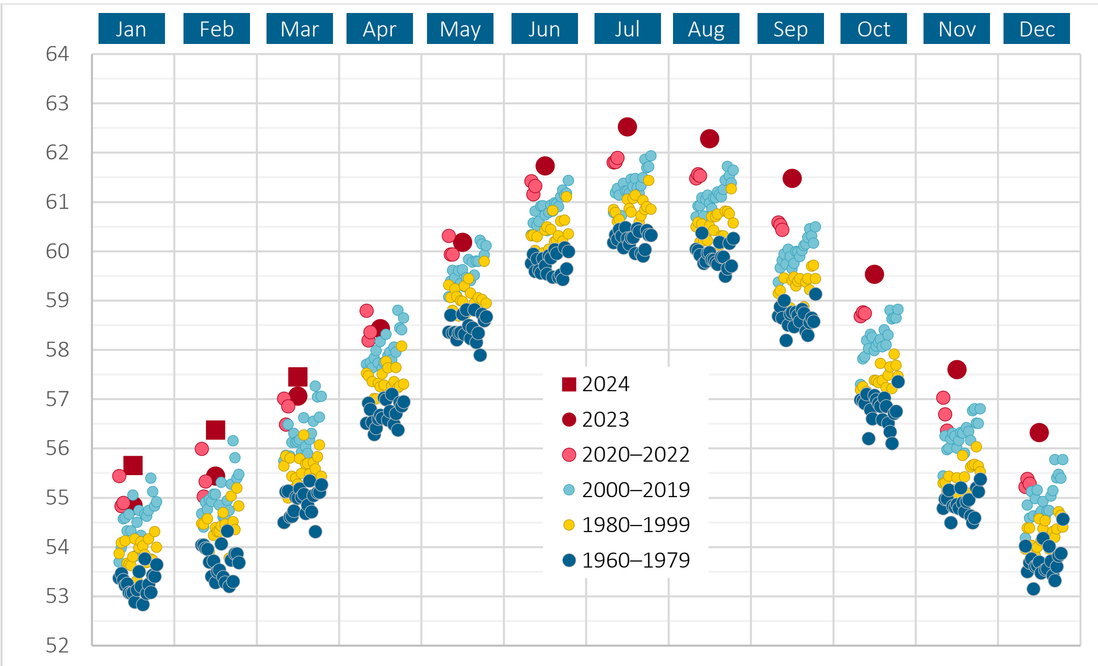
The average global air temperature from April 2023 through March 2024 was 59.13F.

This graph captures ERA5 data through March 2024. The data for February and March 2024 is preliminary and could potentially be revised. Air temperature is measured two meters above the surface of the earth. The ERA5 dataset provides gridded data for over one million locations across the planet's entire surface. The final section of this report describes the methodology for averaging the gridded data to produce global average temperature.

Figure 1 reveals a strong upward trend in global average air temperature. A regression fitted to data from 1960 to 2024 has an R-squared of 88%, and a slope of 0.032 degrees Fahrenheit, which is equivalent to a one-degree increase every 31.1 years. The 95% confidence interval for years-elapsed-per-one-degree-increase runs from 28.3 to 34.5. In other words, the slowest rate of global warming suggested by the data is a one-degree Fahrenheit increase every 34.5 years. The record-high average temperature for the 12 months ending in March 2024 is attributable to record-high monthly temperatures from June of 2023 through March of 2024, as illustrated in both Figure 2 and Table 1.

Figure 2

GLOBAL AVERAGE AIR TEMPERATURE (F) BY MONTH



Monthly air temperature has been at record-high levels from April 2023 through March 2024.

Table 1

GLOBAL AVERAGE AIR TEMPERATURE FOR THE MOST RECENT 12 MONTHS

1	2	3	4	5	6	7
Month	Temp (F) In Recent Month	Monthly Average Temp (F) 1960 to 2019	Anomaly: Recent Temp Minus Historical Average (F)	Historical Standard Deviation (F)	Anomaly Divided by Standard Deviation	Percentile Ranking Against Data from 1960 to Present
2023-04	58.43	57.35	1.08	0.61	1.78	95.2%
2023-05	60.18	59.04	1.14	0.56	2.04	97.6%
2023-06	61.73	60.31	1.42	0.53	2.67	100.0%
2023-07	62.52	60.78	1.74	0.52	3.31	100.0%
2023-08	62.28	60.53	1.75	0.57	3.07	100.0%
2023-09	61.48	59.29	2.19	0.61	3.59	100.0%
2023-10	59.53	57.44	2.09	0.68	3.06	100.0%
2023-11	57.60	55.51	2.09	0.65	3.23	100.0%
2023-12	56.32	54.31	2.01	0.63	3.19	100.0%
2024-01	55.65	53.88	1.77	0.62	2.84	100.0%
2024-02	56.37	54.37	2.00	0.66	3.01	100.0%
2024-03	57.45	55.61	1.84	0.67	2.77	100.0%

In Figure 2, each circle represents the average global air temperature in a prior month. Red circles represent data for 2023, and red squares represent data for 2024. Table 1 provides greater detail for each of the most recent 12 months. Column 4 displays the monthly temperature "anomaly", equal to the difference between the temperature in 2023 or 2024 and the historical average (1960 through 2019) 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 2023/2024 monthly temperature ranked against historical data for the corresponding calendar month. From June of 2023 through March 2024, the ranking of 100% indicates a record-high temperature; thus, we have experienced ten consecutive months of record-high global average air temperatures.

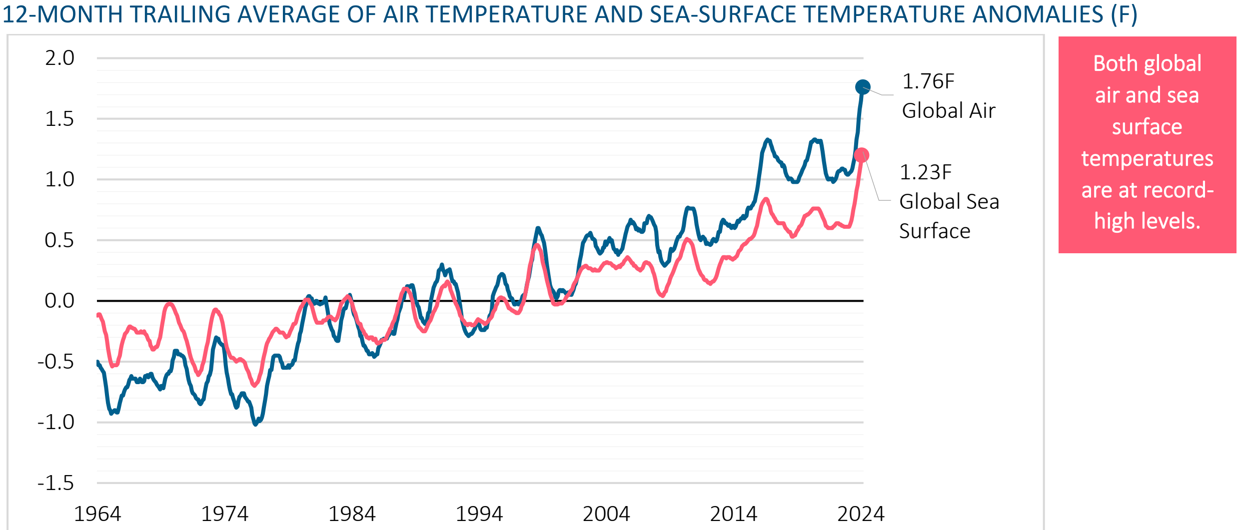
It is worthwhile to briefly explain the seasonal cycle of global average temperature that is apparent in Table 1 and Figure 2. This seasonality may seem counterintuitive given that, on a global level, the earth receives about the same total amount of solar energy per day throughout the year. When the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

Record-High Sea-Surface Temperatures

The recent record-high air temperatures have been accompanied by record-high sea-surface temperatures. As depicted in Figure 3, the 12-month average global sea-surface temperature (SST) from April 2023 through March 2024 was 1.23F above its 1960-2019 average, and global average air temperature was 1.76F above its 1960-2019 average. These are record-highs relative to historical ERA5 data back to 1940. Note that to compute global average SST, climate scientists typically exclude latitudes north of 60N and south of 60S. This report uses the same approach.

Figure 3

12-MONTH TRAILING AVERAGE OF AIR TEMPERATURE AND SEA-SURFACE TEMPERATURE ANOMALIES (F)



In the parlance of climate scientists, temperatures defined relative to their corresponding long-term averages are termed "temperature anomalies". The anomalies in Figure 3 are defined relative to 1960-2019 averages.

Table 2 presents monthly SST data, revealing record-high sea-surface temperatures for 12 consecutive months, from April 2023 through March of 2024. Note that immediately prior to this 12-month period – in March of 2023 – SST was just shy of a record, at the 98th percentile of the historical SST temperature distribution for March.

Table 2

GLOBAL AVERAGE SEA SURFACE TEMPERATURE FOR APRIL 2023 TO MARCH 2024

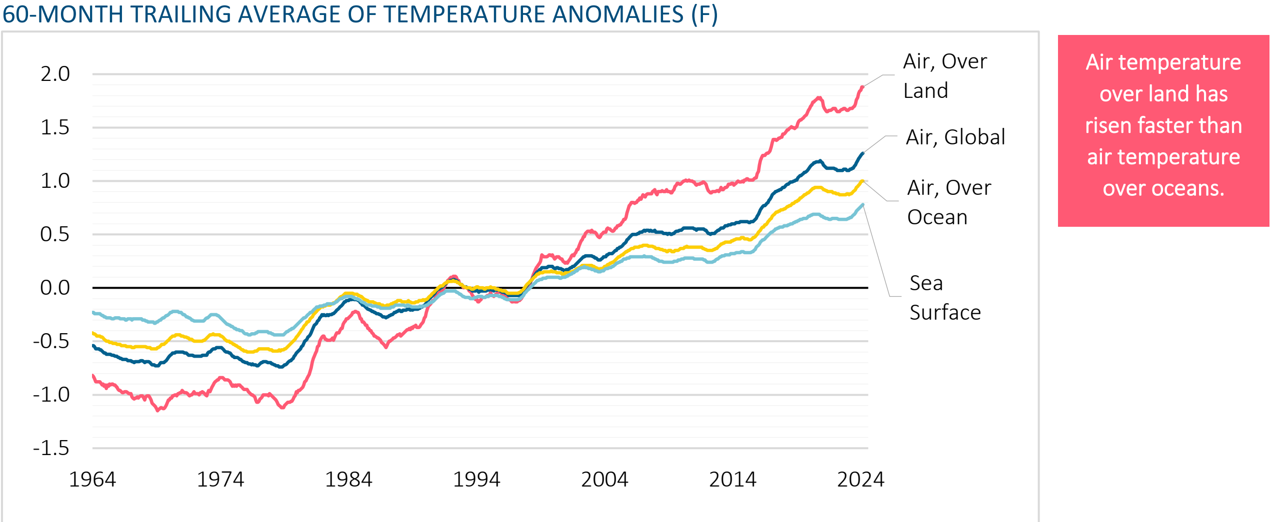
1	2	3	4	5	6	7
Month	**Temp (F) In Recent Month**	**Monthly Average Temp (F) 1960 to 2022**	**Anomaly: Recent Temp Minus Historical Average (F)**	**Historical Standard Deviation (F)**	**Anomaly Divided by Standard Deviation**	**Percentile Ranking Against Data from 1960 to 2022**
2023-04	69.55	68.65	0.90	0.32	2.80	100%
2023-05	69.39	68.46	0.93	0.34	2.70	100%
2023-06	69.46	68.34	1.12	0.36	3.16	100%
2023-07	69.61	68.40	1.21	0.35	3.51	100%
2023-08	69.77	68.48	1.29	0.35	3.66	100%
2023-09	69.65	68.34	1.31	0.37	3.57	100%
2023-10	69.41	68.07	1.34	0.38	3.54	100%
2023-11	69.28	67.95	1.33	0.37	3.60	100%
2023-12	69.41	68.06	1.35	0.36	3.72	100%
2024-01	69.75	68.32	1.43	0.33	4.30	100%
2024-02	69.91	68.59	1.32	0.33	3.99	100%
2024-03	69.93	68.67	1.26	0.36	3.46	100%

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. Given this finding, it is worthwhile to disaggregate the air temperature data into areas over land versus areas over oceans. Figure 4 presents four series of temperature anomalies: (1) global air temperature, (2) air temperature over land areas, (3) air temperature over oceans, bays, and lakes; (4) and sea-surface temperature. To better illustrate long-term trends, Figure 4 shows anomalies averaged across the trailing 60 months rather than 12 months (as was used in Figure 3), revealing that air temperature over land has risen at a significantly faster rate compared to air temperature over the oceans.

Figure 4

60-MONTH TRAILING AVERAGE OF TEMPERATURE ANOMALIES (F)



Note: these anomalies are defined relative to the corresponding 1960-2019 average temperature.

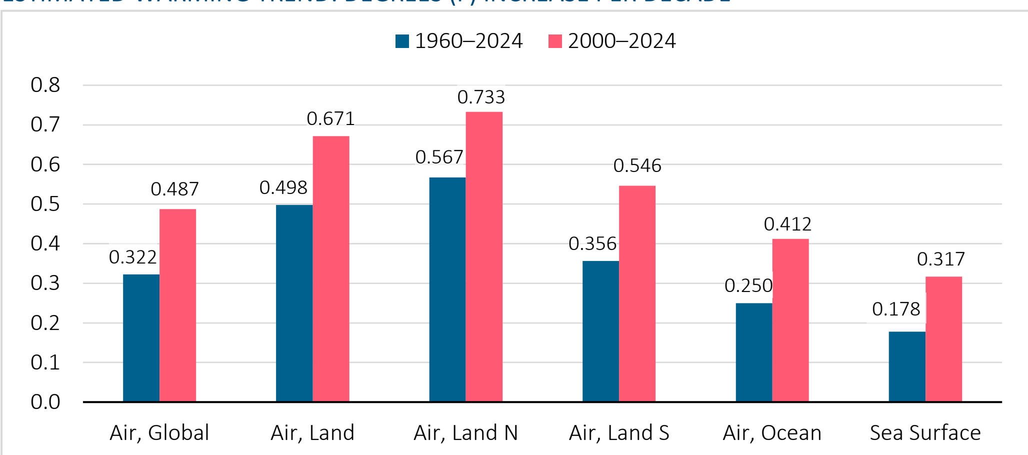
Long-Term Warming Trends

Figures 1, 3, and 4 reveal strong upward trends for both air temperature and sea-surface temperature. Although global warming rates can change across time, it is nevertheless useful to fit a linear regression to the data, thereby producing an estimated rate-of-warming that is constant across time. Regressions were run across two overlapping time periods: (1) 1960 to 2024 and (2) 2000 to 2024. Figure 5 presents the regressions' best estimates for warming trends, while Table 3 presents both the best estimates as well as low and high estimates that together form a 95% confidence interval.

Because the data for 2024 is partial, extending only through March, the first 3 months of 1960 were excluded from the 1960 to 2024 regressions, resulting in 64 complete 12-month periods, from April of 1960 through March of 2024. Similarly, the first 3 months of 2000 were excluded from the 2000 to 2024 regressions, resulting in 24 complete 12-month periods from April of 2000 through March of 2024. The use of complete 12-month periods ensures that the regression is free of any seasonal effects that might be introduced if a partial year of data were used.

Figure 5

ESTIMATED WARMING TREND: DEGREES (F) INCREASE PER DECADE



Data from 2000 to 2024 suggest a possible increase in the pace of global warming.

Note: "Air, Land" is air temperature averaged across all land areas, while "Air, Land N" and "Air, Land S" capture solely the land areas in the northern and southern hemispheres, respectively. "Air, Ocean" is air temperature across all bodies of water. "Sea surface" is the average water temperature across the surface of oceans and other bodies of water.

Table 3

95% CONFIDENCE INTERVAL FOR RATE OF WARMING (DEGREES FAHRENHEIT PER DECADE)

Temperature Data	Time Period	R Squared	Warming Rate (F): Low Est	Warming Rate (F): Best Est	Warming Rate (F): High Est
Air, Entire Earth	1960–2024	87.8%	0.290	0.322	0.353
Air, Entire Earth	2000–2024	79.0%	0.378	0.487	0.596
Air, Over Land	1960–2024	88.0%	0.450	0.498	0.546
Air, Over Land	2000–2024	77.3%	0.512	0.671	0.829
Air, Over Land, Northern Hemisphere	1960–2024	87.2%	0.510	0.567	0.624
Air, Over Land, Northern Hemisphere	2000–2024	72.9%	0.538	0.733	0.927
Air, Over Land, Southern Hemisphere	1960–2024	75.0%	0.302	0.356	0.410
Air, Over Land, Southern Hemisphere	2000–2024	55.7%	0.334	0.546	0.758
Air, Over Oceans	1960–2024	85.3%	0.223	0.250	0.277
Air, Over Oceans	2000–2024	77.6%	0.316	0.412	0.508
Sea-Surface	1960–2024	75.7%	0.151	0.178	0.204
Sea-Surface	2000–2024	69.8%	0.227	0.317	0.408

The regression results indicate the following:

- Global average air temperature over land is increasing at about twice the rate of air temperature over oceans, and at nearly three times the rate of sea-surface temperature.
- Average air temperature over land is increasing at a significantly faster rate in the northern hemisphere compared to the southern hemisphere.
- Warming rates estimated across the 2000-2024 period are significantly greater than those estimated across the 1960-2024 period, suggesting a possible increase in the pace of global warming.

Interactive Temperature Maps Are Available Online

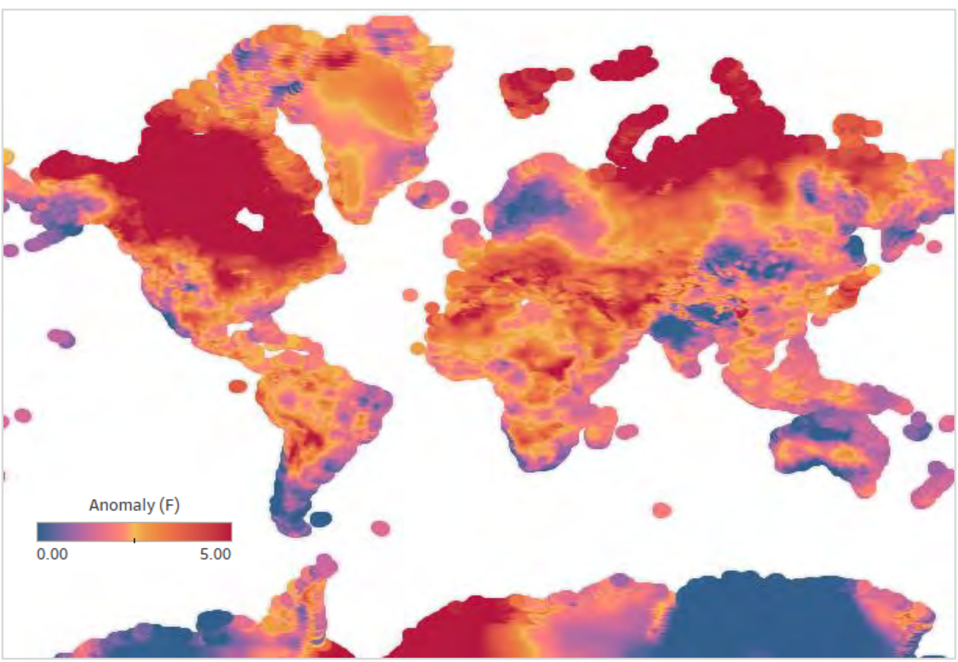
The analysis presented thus far in this report has focused on global average temperatures. The results summarize the macro-level state of the planet but provide no information about temperature in specific regions. Therefore, a Tableau map was created to visualize air temperature data for each ERA5 grid point, and is accessible online:

https://public.tableau.com/views/TemperatureAnomalies_17135526296080/Map?:langu age=en-US&publish=yes&:sid=&:display_count=n&:origin=viz_share_link

This map is focused solely on air-temperature over land areas and has interactive features for presenting temperature anomalies computed across various periods. For example, Figure 6 was produced from the Tableau map by selecting anomalies calculated across April 2023 to March 2024.

Figure 6

AVERAGE TEMPERATURE FROM APRIL 2023 TO MARCH 2024 MINUS AVERAGE FROM 1960 TO 2019 (F)



During April 2023–March 2024, most of Canada, much of Russia, and some of Antarctica were more than 5F above the corresponding average temperatures from 1960–2019.

Figure 6 reveals that during the 12 months from April 2023 to March 2024, most of Canada, a large section of Russia, and some of Antarctica were more than 5F above the corresponding historical averages from 1960 to 2019.

In addition to anomalies computed across the 12-month period from April 2023 through March 2024, the interactive map can also show anomalies calculated across the following periods: the 3-year period from April 2021 through March 2024, the 5-year period from April 2019 through March 2024, and the 10-year period from April

2014 through March 2024. A toggle switch is available to change the map display from one of these periods to another.

Note that the anomalies in Figure 6 were calculated separately for each ERA5 grid point. For example, consider the grid point at 39N 77W, which is located just outside of Washington DC. During the 1960 to 2019 reference period, this location experienced an average temperature of 56.02F, according to ERA5 data. From April 2023 to March 2024, its average temperature was 58.53F, which equates to an anomaly of 2.51F (the difference between 58.53F and 56.02F).

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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