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Human influence can explain the widespread exceptional warmth in 2023

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Attribution of the record-shattering global annual heat in 2023 to human and/or natural factors is fundamentally required for reliable predictions of upcoming global warming and its impacts. An observation-model comparison of global hot areas supports a key role for human-induced climate change, with a small contribution from El Niño.

The World Meteorological Organization has confirmed that "2023 is the warmest year on record, by a huge margin", with exceptionally high sea surface temperatures around the globe and the lowest Antarctic sea ice extent on record[1]. According to the report, 2023 annual average global temperature was 1.45 ± 0.12 °C above pre-industrial levels (1850–1900). This is 0.16 °C higher than the previous record in 2016, approaching the Paris Agreement limit of 1.5 °C. The record-shattering global annual heat in 2023 was beyond our expectation and brought unprecedented extreme weather events across the globe including heatwaves, heavy rainfall events, droughts, and wildfire[2]. For more reliable prediction of upcoming future climates and associated impacts, it is imperative to identify human and natural factors and mechanisms behind the 2023 unprecedented heat and quantify their relative contributions. Important questions will include whether 2023 was just an outlier year due to El Niño and other natural factors like the Hunga Tonga eruption, or whether 2023 temperatures mark a beginning of a new normal state as the result of anthropogenic warming.

Potential contributors

There are a few potential contributors to the unusually warm year 2023. Anthropogenic factors include background long-term global warming in response to increasing atmospheric greenhouse gas concentrations. Reduced sulphate aerosol loading in the atmosphere as a result of ship emission regulations[3] is a potential contributing factor, but probably only in the hundreds of a degree globally[4], insufficient to explain the abrupt increase in global sea surface temperature in 2023.

Important natural factors include El Niño and the Hunga Tonga eruption. The Hunga Tonga–Hunga Ha'apai eruption in 2022 has been suggested to explain some of the 2023 extreme warmth. Unlike more common sulfur-rich volcanic eruptions, the Hunga Tonga eruption injected large amounts of water vapour into the stratosphere and thereby could enhance tropospheric warming[5]. However, its net contribution to global temperature remains to be determined, including careful consideration of the associated aerosol responses[6].

El Niño modulates global mean temperature on interannual to interdecadal time scales and extreme El Niño events can raise the global temperature by 0.2 °C above the long-term trend line[7,8]. After a triple-dip La Niña, an El Niño event emerged from July 2023 onwards. Its role in the 2023 record warmth needs to be understood, as does its impact on 2024 global temperature: El Niño usually exerts a bigger impact in its decaying year.

Area-based exceptionality

Although global mean temperature is an indicator of global warmth, associated impacts can vary depending on regions. Therefore, the same magnitude of global mean temperature increase can imply very different regional impacts. In this regard, a measure of area or population exposure to the unusual extreme event has been assessed, which can better represent local-scale impacts[9,10]. Here, I assessed the exceptionality of 2023 heat using a simple metric: the fraction of the global area that experienced unusual warmth. In addition, I evaluated human contributions to this warmth by comparing the extent of hot areas in observations with its counterpart in climate model simulations with and without human factors. Finally, I estimated the possible range of El Niño and other natural variability contributions using near-future simulations from the same models. Based on these indicators, anthropogenic global warming likely played a dominant role, explaining at least two-thirds of the unusually large global area of exceptional warmth in 2023.

Unprecedented widespread warming

2023 was exceptional in terms of the size of the area affected by unusual warming. To measure global area with unusual heat, I compiled the area fraction of the global surface where annual average temperature anomalies were larger than two standard deviations using the ERA5 reanalysis data[11]. Figure 1a shows the spatial pattern of annual mean temperature anomalies in 2023 relative to the 1981–2010 averages. Widespread warmth occurred over large parts of both land and ocean. Comparison with the anomaly pattern from 2016, the previous warmest year (Fig. 1b), clearly shows the exceptionality of the 2023 global heat. Aside from the equatorial Eastern Pacific that reflects the developing El Niño, the subtropical North Atlantic, western tropical Pacific, mid-latitude North Pacific, and several mid-latitude Southern Ocean regions exhibit unusual warming exceeding two standard deviations.

Interestingly, 2023 hotspot regions do not overlap with those of 2016, except the western tropical Pacific. Considering that 2016 was the year after the peak of an extreme El Niño event, this difference in hot areas suggests that the contribution from El Niño to the 2023 extreme warmth was small.

Overall, about 42% of the globe experienced heat (defined as more than two standard deviations) in 2023, surpassing the 2016 record of about 32% by a large margin (Fig. 1c). Extreme heat (defined as three standard deviations exceedance) occupied about 13% of the global surface in 2023, almost doubling the 2016 area of about 7%. Area fractions measured for global land or ocean only exhibit similar percentages to the global results (not shown), indicating the strong land-ocean connection. Although individual basin surface temperatures will be affected by region-specific natural variabilities such as the Atlantic Multidecadal Variability for the North

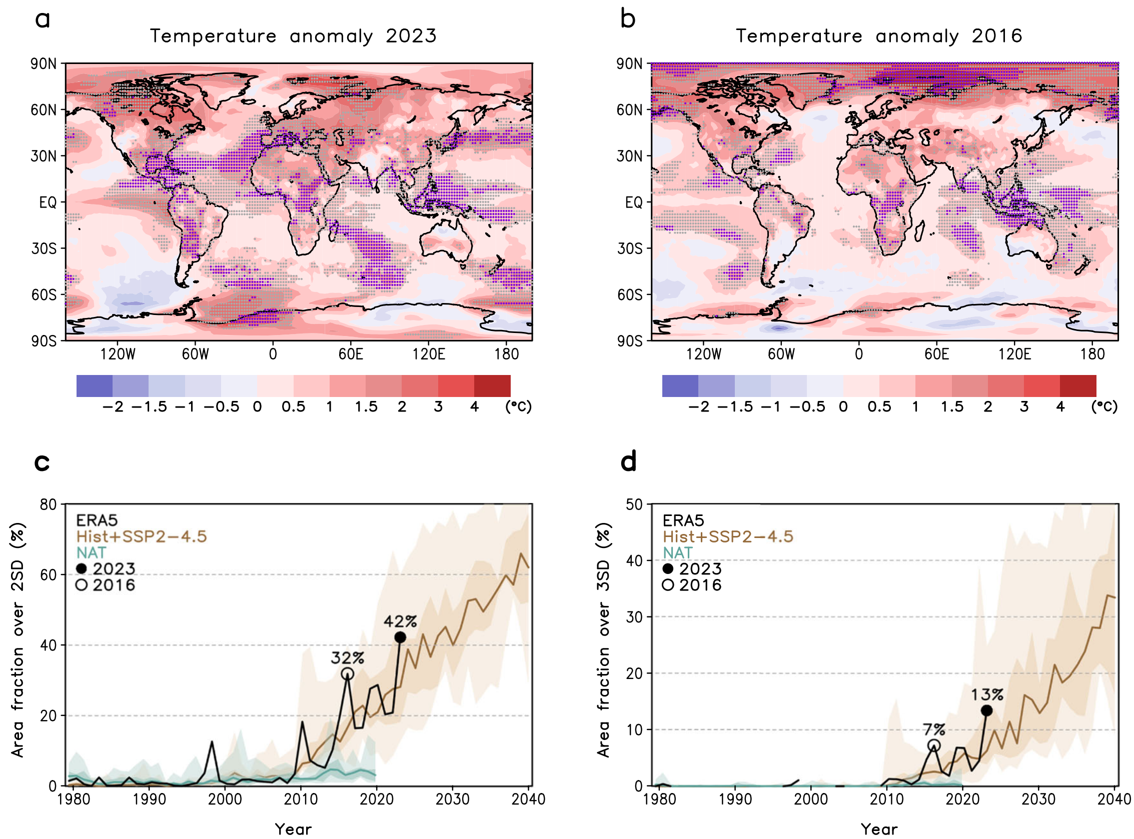

Fig. 1 | Widespread heat. Extremely high annual mean surface air temperature anomalies (relative to the 1981–2010 average) were substantially more widespread for the exceptional year 2023 (**a**) than for the previous record year 2016 (**b**). Data are from ERA5 renanalyses[11]; grey and purple marks indicate grid points with temperature anomalies larger than 2 and 3 standard deviations of annual mean temperatures, respectively. The global area fraction exceeding two (**c**) three (**d**) standard deviations in terms of temperature has been rising in observation-based reanalyses (ERA5; black) as well as in climate model simulations that are run by historical data plus an intermediate emissions scenario (CMIP6 historical plus SSP2-4.5 runs (Hist + SSP2-4.5); brown). By contrast, climate model simulations with only natural forcing (CMIP6 hisNat simulations (NAT); green) show only a very slow expansion of area affected by heat. Black filled and open circles indicate observed values for the year 2023 and 2016, respectively. Solid lines represent multi-model medians and dark and light shadings indicate inter-model inter-quartile and min-max ranges, respectively. CMIP6 simulations include twelve global climate models that provide both experiments (Hist + SSP2-4.5 and NAT): ACCESS-CM2, ACCESS-ESM1-5, BCC-CSM2-MR, CanESM5, CNRM-CM6-1, FGOALS-g3, GFDL-ESM4, HadGEM3-GC31-LL, IPSL-CM6A-LR, MIROC6, MRI-ESM2-0, and NorESM2-LM, with one run per model (typical member r1i1p1f1) used to give equal weighting to each model.

Atlantic[12], strong warming over most of the global ocean basins would not occur in the same year without systematic large-scale influences.

Human versus natural forcing contribution

The question arises whether global climate models capture the observed sudden expansion of heat in 2023. Surprisingly, in simulations that combine historical data up to 2015 with an intermediate emissions pathway (SSP2-4.5) up to 2023, the area fraction for heat (Fig. 1c) and extreme heat (Fig. 1d) follows the observed time series quite well. In these simulations, conducted using twelve Global Climate Models with emissions scenarios that are closely aligned with policies based on the nationally determined contributions to achieving the Paris Climate Goals[13], the area fraction exposed to heat shows steady increases after around 2010 and becomes >30% in 2023. Inter-model ranges cover the observations throughout the time series including the 2023 and 2016 extreme values. Results based on thresholds for extreme heat are also consistent (Fig. 1d).

This agreement between 2023 observations and climate-model simulations implies that the heat observed in 2023 may not be unexpected in view of existing model projections. This holds especially when taking into account that the preceding triple-dip La Niña may have hindered increases of global temperature and hot areas during 2021–2022, which probably contributed to the relatively abrupt warming in 2023. The projections using intermediate emissions scenarios exhibit almost linear increases of hot areas in the future; according to the projections, more than 60% of the area fraction will fall into this category by 2040.

In the multi-model median, a fraction of 42% of the area affected by heat as observed in 2023, occurs around the year 2030, indicating that this event emerged a few years earlier than projected. In contrast to these simulations with both human and natural influences, model runs with only natural influence show only slight temperature increases during the past few decades, reflecting the slow recovery from the Mount Pinatubo eruption in 1991[14,15].

Influence of El Niño and other climate variability

To estimate the influence of El Niño on the 2023 extreme growth of heat area, I examined the relation between annual mean area fractions and the

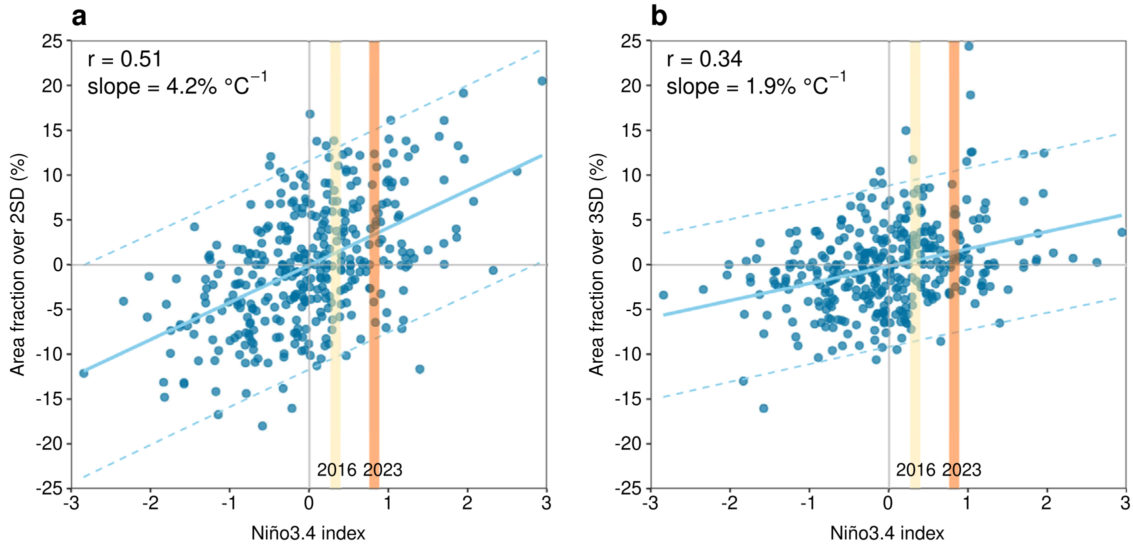

Fig. 2 | El Niño influence on area affected by (extreme) heat. Significant correlations are found between the annual mean Niño3.4 index and the global area fractions with temperatures exceeding two (**a**) and three (**b**) standard deviation in the historical/intermediate scenario climate simulations for the years 2011 to 2040. Global area affected by heat (two standard deviations) expands by about 4% per °C in the Niño3.4 index (**a**), for extreme heat (three standard deviations), the increase is about 2% (**b**). The dashed lines indicate the 95% prediction interval for linear regression. Both Niño3.4 indices and area fractions are detrended for each model simulation prior to analysis. Vertical lines indicated the observed Niño3.4 values for 2023 and 2016.

annual mean Niño3.4 index—an indicator of El Niño strength—for the period 2011 to 2040. Looking again at the intermediate scenario (SSP2-4.5) simulations from the same twelve models as above, it emerges that during El Niño years areas affected by heat and extreme heat tend to expand by about 4% and 2%, respectively, per 1 °C increase in the Niño3.4 index (Fig. 2a, b). According to this relation, the influence of 2023 El Niño with Niño3.4 index of 0.82 °C on the global area fraction affected by heat would be very small, around 3.4%. Even for the 2015 El Niño—with a Niño3.4 index of 1.46 °C one of the strongest El Niño events—global areas exposed to heat increase by just over 6%. These model-observation comparisons are a tentative first estimate; large uncertainties remain across different years and different model simulations (see dashed lines in Fig. 2), and other internal variabilities can potentially explain up to ±12% of area fractions for heat. Combined, El Niño and other climate variabilities may have contributed the observed 2023 expansion of the area affected by heat up to about 15%—which would leave around 27% that are likely to be dominated by anthropogenic global warming. Uncertainties for extreme heat areas are larger, because of the small sample size.

Avenues for exploration

This quick assessment using an area-based metric suggests that anthropogenic warming had dominant role in the exceptional widespread heat recorded in 2023. This metric captures the observed abrupt expansion of unusual heat into both land and ocean in line with global warming. Yet, the mechanisms responsible for regional and seasonal warming patterns remain to be determined. In particular, accelerated warming in the subsurface North Atlantic and Southern oceans has been suggested as a key player in shaping the 2023 exceptionality[12]. Subsurface warming in the Southern Ocean could also have led to the exceptional decrease of Antarctic sea ice and possibly triggered a shift to a new low-sea-ice-extent state[16].

Various atmospheric and oceanic mechanisms could induce the rapid warming of the ocean's surface layer regionally. This could include changes in radiative forcing, for example through lower levels of Saharan dust, or reduced ship-emitted sulphate aerosols. Changes in heat fluxes and transport by atmospheric and ocean circulation patterns are other possibilities, including the finding that prevalence of a zonal wave number 3 pattern accompanied the extreme Southern Ocean warming and the record-low Antarctic sea ice[17].

To better understand upcoming changes in global and regional temperatures and associated risks of extreme events, it is urgently required to quantify relative and combined contributions of the individual mechanisms to the 2023 exceptionality and also to identify their anthropogenic or natural origins.

Data availability

The ECMWF Reanalysis v5 (ERA5) data is available at https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5. All the CMIP6 model simulation data are publicly available at https://esgf-node.llnl.gov/projects/cmip6/.

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Author contributions

S.K.M. conceptualized the study and wrote the manuscript.

Competing interests

The author declares no competing interests.

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