Global Human Fingerprints on Daily Temperatures in 2022

Daniel M. Gilford[a], Andrew J. Pershing[a], Joseph Giguere[a], and Friederike E. L. Otto[b]

[a] *Climate Central, Princeton, NJ, USA*

[b] *Grantham Institute of Climate Change, Imperial College London, UK*

Corresponding author: D. M. Gilford, dgilford@climatecentral.org

Capsule summary. Extreme temperatures in the UK (July 2022) and India/Pakistan (Spring 2022) are confidently attributed to climate change using an automated system. Similarly attributable extremes occurred frequently worldwide in 2022.

1. Introduction

2022 was an exceptional year for heat worldwide. Heat-related disasters worsened droughts and forest fires, and threatened millions of people's health (EM-DAT 2008; Ballester et al. 2023). While human-induced climate change is no doubt responsible for the globally-increasing rate and intensity of extreme heat (Masson-Delmotte et al. 2021), there is an ongoing need to investigate and communicate the extent of this human influence depending on time of year, region, and event persistence (Swain et al. 2020).

The rapid advancement of climate attribution science is enabling quantitative and confident attribution of human influences on the likelihood of individual heat events within days of occurrence (National Academies of Sciences 2016; Masson-Delmotte et al. 2021; Clarke et al. 2022). The World Weather Attribution Initiative (WWA) has pioneered rapid attribution approaches, and regularly publishes detailed attribution reports of specific events using peer-reviewed methods (e.g. Philip et al. 2020). These self-consistent reports reliably inform which 2022 heat events were potentially most noteworthy and attributable (World Weather Attribution Initiative 2023; Otto and Raju 2023). But WWA's in-depth studies require limited resources and days-to-weeks to produce, which restricts the number of heat events that can be assessed and attributed over a given year.

A new automated attribution system has been developed to enable real-time climate attribution of heat events every day, everywhere (G22; Gilford et al. 2022). We implement this system to expand on WWA's capacity, producing a hindcast of daily attribution estimates for globally-resolved air temperatures in 2022. We also evaluate the system by comparing with WWA reports for two events: a 2-day event over the UK (July 2022) and a 2-month-long event over India/Pakistan (Mar/Apr 2022). Using these as a benchmark, we demonstrate the attributable scale and spatial-temporal scope of similarly-defined events around the world in 2022.

2. Approach and Data

We quantify the attributable climate influence on observed daily and multi-day temperatures with a metric called the "Change in Information due to Perspective" (ChIP) based on the definition of Shannon information content from information theory (MacKay 2003; Pershing et al. 2023). ChIP compares the occurrence likelihood of daily temperature, T, in the modern climate (P_{mod}; +1.27 K global mean air temperature since pre-industrial) with that from a counterfactual climate without greenhouse gas emissions (P_{cf}; +0 K),

$$\text{ChIP}(T) \equiv log_2[P_{mod}(T) \; / \; P_{cf}(T)\;] \qquad (1)$$

ChIP has several advantages compared to traditional attribution metrics. The occurrence ratio in Eq. (1) considers changes in the likelihood of *observing* T, rather than commonly-employed "probability ratios" (PRs; e.g. Philip et al. 2020) that consider changes in the likelihood of *exceeding* T. This approach enables attribution assessments for not only extremely hot days, but all days, allowing negative ChIP values to be assigned to conditions made less likely by climate change. Furthermore, ChIP's logarithmic form allows its daily values to be averaged or summed, providing a meaningful attribution estimates for multi-day events. We use this feature to derive a variance-scaled ChIP that can be directly compared with WWA's PRs estimated from multi-day mean temperatures.

To derive variance-scaled ChIP, we assume temperatures are normally distributed, and the likelihood of T is given by $P \sim \mathcal{N}(\mathrm{T}, \mu, \sigma)$, with mean, μ, and standard deviation, σ. The attributable change in likelihood between modern and counterfactual periods can then be described by a change in the mean, $\mu + \delta$, where δ is linearly related to attributable GMT changes in the framework's median method (Supplementary Materials). Rewriting Eq. (1):

$$\mathrm{ChIP}(T) \simeq log_2[\, \mathcal{N}_{mod}(T, \mu + \delta, \sigma) \,/\, \mathcal{N}_{cf}(T, \mu, \sigma)\,] \tag{2}$$

$$\simeq -\frac{\delta}{2ln(2)\sigma^2}(2\mu + \delta - 2T) \tag{3}$$

Assuming μ, δ, and daily σ are representative over an n-day period, then the ChIP of n-day average temperatures ($\bar{T} = (1/n)\sum_{j=1}^{n} T_j$) is,

$$\mathrm{ChIP}_n(\bar{T}) = \left(\frac{\sigma^2}{{\sigma_n}^2}\right)\overline{ChIP}(T_j) \tag{4}$$

where σ_n is the standard deviation of the n-day means. The resulting variance-scaled ChIP, $ChIP_n(\bar{T})$, quantifies climate change's attributable influence on multi-day average temperatures.

We implement G22's multi-method attribution framework (Gilford et al. 2022; Pershing et al. 2023; Supplemental Materials) following established attribution protocols (Philip et al. 2020) to create a 2022 daily hindcast of ChIP and $\mathrm{ChIP}_n(\bar{T})$ around the world. The multi-method approach uses observed trends from ERA5 (Hersbach et al. 2020) and climate simulations from CMIP6 (Eyring et al. 2016) to generate an ensemble of modern and counterfactual distributions. For each observed daily 2m maximum (T_{max}), average (T_{avg}), and minimum air temperature (T_{min}) we calculate empirical- and model-derived P_{mod} and P_{cf}, which are synthesized to produce a ChIP for each daily temperature observation in 2022.

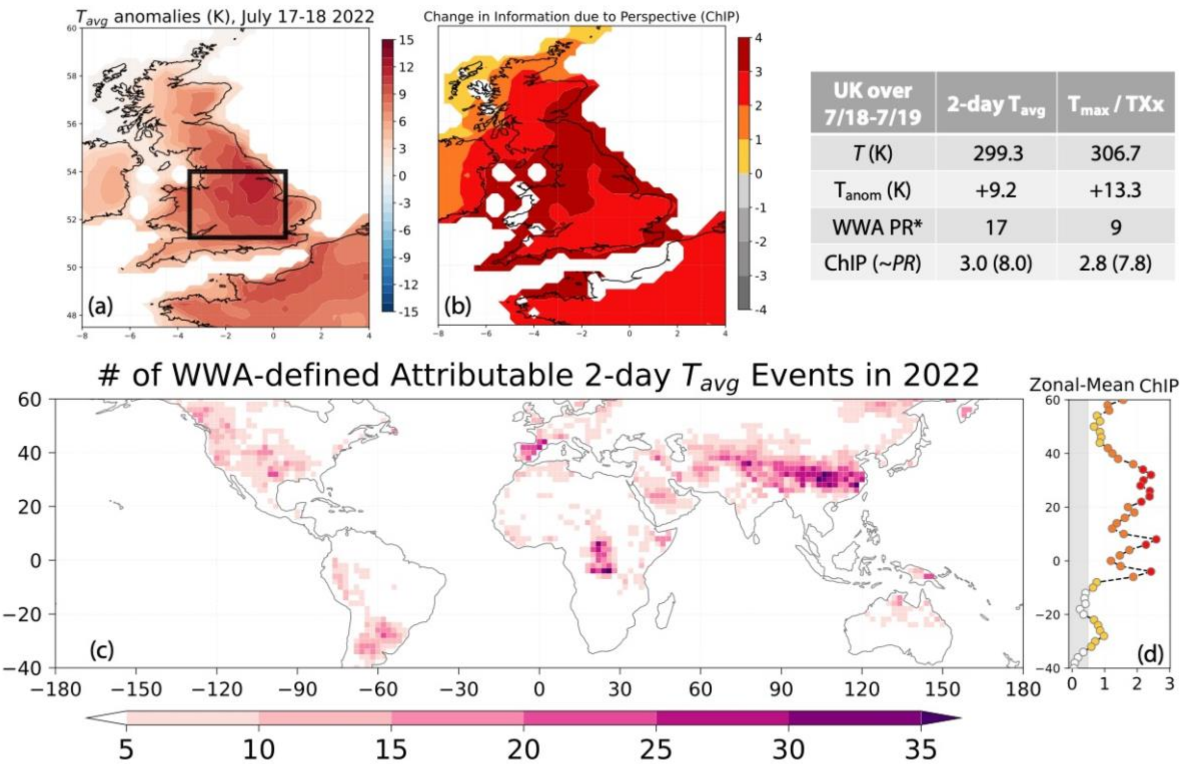

Fig. 1. 17-18 July 2022 (a) average temperature anomalies and (b) the associated Change in Information due to Perspective (ChIP; i.e. this study's daily attribution estimate). The accompanying table includes temperatures (the defining basis for similar extreme events, see text) and compares World Weather Attribution range of *lower bound probability ratios against this study's ChIP estimates and the equivalent PR. (c) Number of 2-day average temperatures in 2022 consistent with the WWA UK event definition in each 2°×2° land pixel, and (d) the zonal-mean ChIP across these 2-day events.

3. Results

Figure 1 summarizes analyses of United Kingdom's 2-day extreme heat event during 17-18 July 2022. WWA analyzed two extreme event definitions averaged over the region (black box): the 2-day mean T_{avg} and the annual maximum of T_{max}. Both metrics were observed above their 1991–2020 climatological 99th percentiles.

Mean ChIP values during the UK event were 3.0 (T_{avg}) and 2.8 (T_{max}), indicating the extreme temperatures were made 8× more likely because of climate change. This equivalent ratio is smaller than WWA's final PR estimate (10×), but under near-record temperatures the underestimate is consistent with G22's conservative system design. Because ChIP is constructed from occurrence likelihoods, the ratio in Eq. (1) will always be lower than the PR. Secondly, to enable autonomous real-time attribution, G22's framework evaluates a continuous skew-normal fit across each temperature distribution rather than using extreme value theory in the tails (e.g., van Oldenborgh et al. 2021). This effectively bounds reliable ChIP calculations, because tail probabilities will be undersampled and hence uncertain. Pershing et al. (2023) codifies this limitation by fixing an absolute upper bound of $|ChiP| \leq 4$ on each method's output, so the maximum equivalent PR is 16 (if the empirical- and model-based methods both reach this maximum). Altogether, while ChIP values are often a conservative underestimate, results agree with WWA that human-caused climate change made the UK event much more likely. Note that daily ChIP average standard errors—estimated from the spread of CMIP6 simulations and regression uncertainties between local temperatures and GMT (Supplementary Materials)—are <0.5 on 0.3% of days/locations in 2022 (not shown); e.g., the 40S–60N mean standard error during July 17-18 was 0.22.

To screen for comparable events in 2022, we regrid temperature and ChIP to a resolution comparable to the UK event (2°×2°, black box Fig. 1a) and then search for when/where 2-day rolling-mean T_{avg} values exceeded their 1991–2020 climatological 99th percentile. Without a climate shifted distribution we would expect 3.7 exceedances per year, but globally we find these events were much more common in 2022. Hotspots with 20+ events include central/west N. America, Argentina/Paraguay, central Africa, western Europe, China, and

Papua New Guinea. These events were robustly attributable (ChIP > 0.5, shading Fig. 1c) with some reaching the maximum (ChIP = 4.0). Zonal-mean ChIP over these hotspots was typically between 1 and 2.5.

Figure 2 summarizes analyses of India and Pakistan's 2-month-long extreme heat during March/April 2022. Two-month-average daily T_{max} anomalies peaked during the second warmest March/April since 1991, ranging from +1 K to +6 K across the averaging region (black polygon Fig. 2a); concurrent $\mathrm{ChIP}_n(\bar{T})$ reached 16.0 along India's northwest coastal region and $\mathrm{ChIP}_n(\bar{T}) \sim 5$ stretched into the interior during the event. $\mathrm{ChIP}_n(\bar{T}) = 16$ implies that the 2-month average temperature was made 65,536× more likely because of climate change. Region-average equivalent PRs show these event anomalies were $2^{(3.1)}$ = 8.6× more likely because of human-caused climate change, lower than the average but falling within the range of WWA PR estimates, 30× (2-140×). Despite cooler anomalies during the remainder of 2022, 2-month-average T_{max} was robustly attributable throughout the year; this result implies that the signal of climate change in India/Pakistan 2-month-mean temperatures has effectively emerged from the baseline climate.

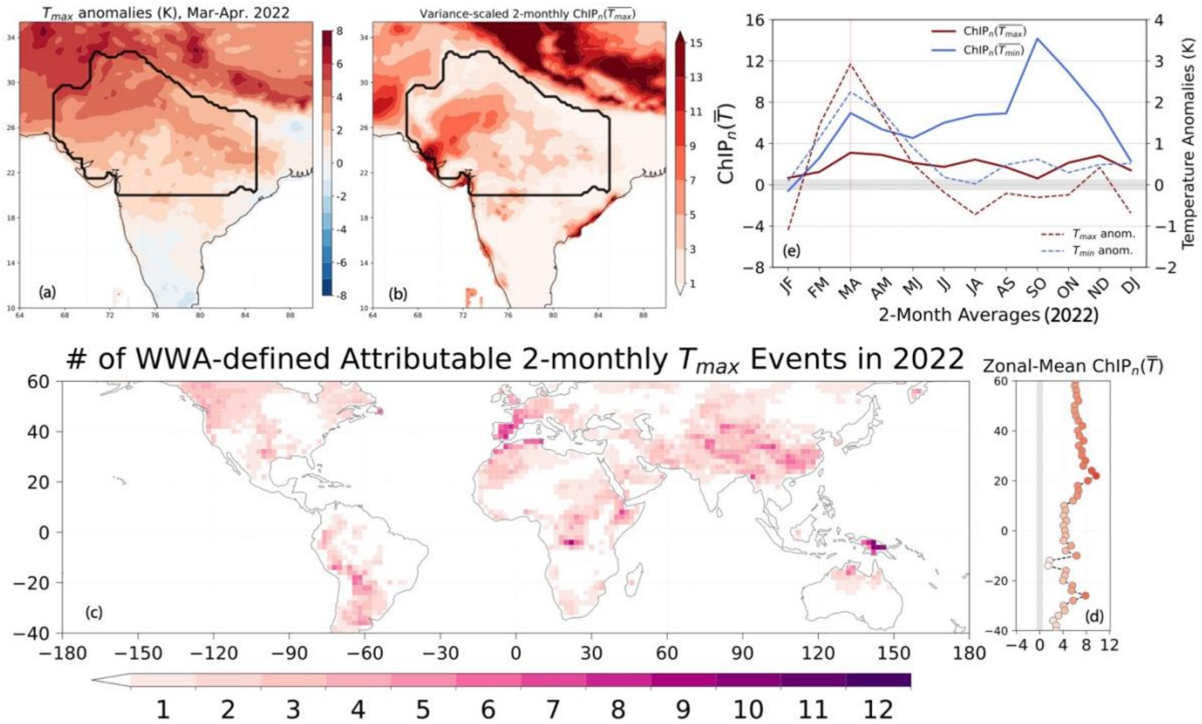

Fig. 2. March/April-mean 2022 (a) maximum temperature anomalies and (b) the associated variance-scaled ChIP. (c) Number of 2-monthly-mean maximum temperatures in 2022 (of twelve 2-monthly periods, Jan-Feb. through Dec-Jan.) consistent with the WWA India/Pakistan event definition (see text) in each 2°×2° land pixel, and (d) the zonal-mean variance-scaled ChIP associated with these events. (e) The 2022 seasonal cycle of 2-monthly-mean maximum (red lines) and minimum (blue lines) temperature anomalies (dashed lines) and the zonal-mean variance-scaled ChIP levels across these 2-month events (solid lines).

To find events similar to the WWA event definition, we search for places and periods around the world where the rolling 2-monthly-average temperatures in 2022 were ranked in the top two since 1991. The mapped number of monthly-pair events meeting this criteria (out of 12) shows many places globally where persistent heat stretched across multiple months. The most prominent hotspots include south-central US, western Europe, Mediterranean coasts, central and eastern Africa, most of China, northern Australia, and Papua New Guinea. $\mathrm{ChIP}_n(\bar{T})$ estimates indicate these events are strongly attributable, consistently averaging ≥ 4.0.

We also examined estimates of attributable T_{min} over India/Pakistan. Despite cooler anomalies overall, regionally-averaged $\mathrm{ChIP}_n(\bar{T})$ estimates of 2-monthly T_{min} are reliably larger than those of T_{max} (except in Jan/Feb), with a regional average of 7.0 in March/April (i.e. made 128× more likely by climate change). In September/October, cooler overall T_{min} values had attribution estimates of equivalent PR > 18,000×, consistent with climate change's strong overnight influence (Karl et al. 1993; Doan et al. 2022).

4. Discussion

A hindcast attributing daily 2022 temperatures to human-caused climate change shows that the WWA definitions of short- (2-day) and long-lived (2-month) extreme temperature events were both relatively common across the globe and highly attributable. Using WWA event definitions, this study demonstrates good agreement between WWA attribution estimates and the Gilford et al. (2022) automated attribution system over two distinct extreme heat events: a 2-day event over the UK (July 2022) and a 2-month-long event over India/Pakistan (Mar/Apr 2022). While the framework's conservative design often underestimates the climate influence compared with WWA's numbers, we find the approach is capable of rapidly identifying and confidently attributing these events. It has also been extended to evaluate similar events on a daily, global basis, and can serve as an early-warning system to support immediate climate change communications.

There are clear and robust human fingerprints on 2022's daily weather. For instance, our results expose the powerful emergence of human influence on overnight temperatures, a well-known (but often under-communicated and under-studied) result of climate change with potentially critical impacts on global health and economics (Roye et al. 2021; Wang et al. 2022; Kim et al. 2023; He et al. 2022). While a thorough examination of the negative impacts associated with these events is beyond our scope, multiple lines of early evidence indicate that widespread attributable heat had human consequences during 2022 (e.g. Ballester et al. 2023; Tobias et al. 2023). Our analyses reveal that there are still many outstanding opportunities to study and communicate attributable temperature events throughout the world each year.

Acknowledgments.

Funding provided by the Bezos Earth Fund, Eric and Wendy Schmidt Fund for Strategic Innovation/The Schmidt Family Foundation, High Meadows Foundation, and the William and Flora Hewlett Foundation.

Data Availability Statement.

Hindcast data will be published in a Zenodo repository upon publication.

REFERENCES

Ballester, J., and Coauthors, 2023: Heat-related mortality in europe during the summer of 2022. *Nature Medicine*, **29 (7)**, 1857–1866, doi:10.1038/s41591-023-02419-z, URL https://doi.org/10.1038/s41591-023-02419-z.

Clarke, B., F. Otto, R. Stuart-Smith, and L. Harrington, 2022: Extreme weather impacts of climate change: an attribution perspective. *Environmental Research: Climate*, **1 (1)**, 012 001, doi:10.1088/2752-5295/ac6e7d.

Doan, Q. V., F. Chen, Y. Asano, Y. Gu, A. Nishi, H. Kusaka, and D. Niyogi, 2022: Causes for Asymmetric Warming of Sub-Diurnal Temperature Responding to Global Warming. *Geophysi-cal Research Letters*, **49 (20)**, 1–11, doi:10.1029/2022GL100029.

EM-DAT, 2008: Em-dat: The international disaster database. Available at: http://www.emdat.be/ Database/Trends/trends.html.

Eyring, V., S. Bony, G. A. Meehl, C. A. Senior, B. Stevens, R. J. Stouffer, and K. E. Taylor, 2016: Overview of the coupled model intercomparison project phase 6 (cmip6) experimental design and organization. *Geoscientific Model Development*, **9 (5)**, 1937–1958, doi:10.5194/ gmd-9-1937-2016, URL https://gmd.copernicus.org/articles/9/1937/2016/.

Gilford, D. M., A. Pershing, B. H. Strauss, K. Haustein, and F. E. L. Otto, 2022: A multi-method framework for global real-time climate attribution. *Advances in Statistical Climatology, Meteorology and Oceanography*, **8 (1)**, 135–154, doi:10.5194/ascmo-8-135-2022, URL https: //ascmo.copernicus.org/articles/8/135/2022/.

He, C., and Coauthors, 2022: The effects of night-time warming on mortality burden under future climate change scenarios: a modelling study. *The Lancet Planetary Health*, **6 (8)**, e648– e657, doi:10.1016/S2542-5196(22)00139-5, URL http://dx.doi.org/10.1016/S2542-5196(22) 00139-5.

Hersbach, H., and Coauthors, 2020: The era5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, **146 (730)**, 1999–2049, doi:https://doi.org/10.1002/qj.3803, URL https: //rmets.onlinelibrary.wiley.com/doi/abs/10.1002/qj.3803.

Karl, T. R., and Coauthors, 1993: Asymmetric Trends of Daily Maximum and Minimum Temperature. *Bulletin of the American Meteorological Society*, **74 (6)**, 1007–1023, doi: 10.1175/1520-0477(1993)074 1007:ANPORG 2.0.CO;2.

Kim, S. E., M. Hashizume, B. Armstrong, A. Gasparrini, K. Oka, Y. Hijioka, A. M. Vicedo-Cabrera, and Y. Honda, 2023: Mortality risk of hot nights: A nationwide population-based retrospective study in japan. *Environmental Health Perspectives*, **131 (5)**, 057 005, doi:10.

1289/EHP11444, URL https://ehp.niehs.nih.gov/doi/abs/10.1289/EHP11444, https://ehp.niehs. nih.gov/doi/pdf/10.1289/EHP11444.

MacKay, D. J. C., 2003: *Information Theory, Inference, and Learning Algorithms*. Copyright Cambridge University Press.

Masson-Delmotte, V., and Coauthors, 2021: Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1–3949 pp., URL https://www.ipcc.ch/report/ sixth-assessment-report-working-group-i/.

National Academies of Sciences, 2016: *Attribution of Extreme Weather Events in the Context of Climate Change*. 186 pp. pp., doi:10.17226/21852, URL http://nap.edu/21852.

Otto, F. E. L., and E. Raju, 2023: Harbingers of decades of unnatural disasters. *Communications Earth & Environment*, **4 (1)**, 280, doi:10.1038/s43247-023-00943-x, URL https://doi.org/10. 1038/s43247-023-00943-x.

Pershing, A. J., K. L. Ebi, D. M. Gilford, J. Giguere, B. W. Placky, and B. H. Strauss, 2023: Beyond extremes: quantifying the exposure of people and ecosystems to climate-driven heat every day, everywhere. *PNAS*, under review.

Philip, S., and Coauthors, 2020: A protocol for probabilistic extreme event attribution analyses. *Advances in Statistical Climatology, Meteorology and Oceanography*, **6 (2)**, 177–203, doi: 10.5194/ascmo-6-177-2020.

Roye, D., and Coauthors, 2021: Effects of hot nights on mortality in southern europe. *Epidemiology*, **32 (4)**, URL https://journals.lww.com/epidem/fulltext/2021/07000/effects of hot nights on mortality in southern.5.aspx.

Swain, D. L., D. Singh, D. Touma, and N. S. Diffenbaugh, 2020: Attributing Extreme Events to Climate Change: A New Frontier in a Warming World. *One Earth*, **2 (6)**, 522–527, doi: 10.1016/j.oneear.2020.05.011, URL https://doi.org/10.1016/j.oneear.2020.05.011.

Tobias, A., D. Roye, and C. Iniguez, 2023: Heat-attributable mortality in the summer of 2022 in spain. *Epidemiology*, **34** **(2)**, URL https://journals.lww.com/epidem/fulltext/2023/03000/heat attributable mortality in the summer of 2022.19.aspx.

van Oldenborgh, G. J., and Coauthors, 2021: Pathways and pitfalls in extreme event attribution. *Climatic Change*, **166** **(1)**, 13, doi:10.1007/s10584-021-03071-7, URL https://doi.org/10.1007/ s10584-021-03071-7.

Wang, Y., X. Shen, M. Jiang, S. Tong, and X. Lu, 2022: Daytime and nighttime temperatures exert different effects on vegetation net primary productivity of marshes in the western songnen plain. *Ecological Indicators*, **137**, 108 789, doi:https://doi.org/10.1016/j.ecolind.2022.108789, URL https://www.sciencedirect.com/science/article/pii/S1470160X22002606.

World Weather Attribution Initiative, 2023: Heatwave Reports. [Accessed 17-08-2023], https://www.worldweatherattribution.org/analysis/heatwave/.