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Heat extremes linearly shift with global warming, with frequency doubling per decade since 1979

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Abstract

Heat extremes have been increasing both in frequency and in intensity in most land regions of the world, and this increase has been attributed to human activities. In the last decade, many outstanding and record shattering heat extremes have occurred worldwide, triggering fears of a nonlinear behaviour or an “acceleration” in the development of heat conditions, considering the warming level when the event occurred. Here we show that the evolution of yearly temperature maxima, with return periods above 10 years, consistently shifts with global temperatures and does not significantly depart from this behaviour in recent years or decades when considered globally or at the scale of continents. This result is obtained by using a classical statistical event attribution technique, where the assumption that the distribution of block-maxima extremes linearly shifts with global warming is tested across years and world land regions. However, the pace of frequency change is large, with the probability of heat extremes exponentially rising and nearly doubling every decade since 1979, particularly when considering events with a return period of about 10 to 50 years in 2000. This makes the climate of a decade ago unrepresentative of today’s climate. Our results overall mean that we do not expect events like the recent outstanding extremes to undergo nonlinear changes, despite fast changes. They also show that assumptions underlying attribution techniques used in many recent studies are consistent with recent temperature trends.

Keywords: extreme heat, climate change, return period

1. Introduction

In recent years, many outstanding climate extremes have been witnessed, with large impacts. Twenty years after the development of pioneering concepts (Allen et al., 2003; Stone and Allen, 2005), event attribution methodologies (Stott et al., 2016) have been applied in an increasingly systematic way in order to assess links between these extremes and climate change. These methods recently led to near-real time applications (Philip et al., 2021; see also <https://www.worldweatherattribution.org>). Short heatwaves or unusually hot months or summers have been analysed since the major European heatwaves of 2003 and 2010. For long events, some large return periods (RPs) were found, eg. ~250 years for the 2010 outstanding heatwave (Otto et al., 2012), even accounting for the change in likelihood due to warming, with large uncertainties. Due to the larger

variability for short events, short heat events were found with lower return periods (see eg. Hannart et al., 2014; Sippel et al., 2015; Kew et al., 2019). For reference, Table 1 shows the events studied and published by the World Weather Attribution (WWA) network between 2015 and 2023 (<https://www.worldweatherattribution.org>).

In the last few years, outstanding heat extremes have occurred, with return periods estimated to exceed 50 to 100 years. The most striking example was the June 2021 Western North America record shattering heatwave that brought temperatures 4°C to 5°C beyond previous records over large areas. For this case, a rapid study was conducted and authors raised the question whether such an event could be explained with classical statistics or whether new processes could have taken place, making it hard to use such methods to estimate stable statistics with current observations (Philip et al.,

2022). Under the assumption that this former possibility held, a return period in the order of ~1000 years in the current climate was found for this specific event. Since then, six of the events studied by WWA have had an estimated return period exceeding 100 years.

Table 1 : Extreme heat events analysed by the World Weather Attribution network, with estimated return periods and references, as of January 2024

Event	Return Period Estimates (current climate)	Reference
Jul 2015, Western Europe	2yr-20yr	Sippel et al., 2016
May 2016, India	7-10yr	van Oldenborgh et al., 2018
Summer 2017, Southern Europe	10yr	Kew et al., 2019
May-Jul 2018	5-10yr	WWA, 2018 ; Yiou et al., 2020
Jun 2019, France	30 yr	Vautard et al., 2020
Jul 2019, Netherlands, France, Germany	10yr to 150 yr depending on location	Vautard et al., 2020
Jan-Jun 2020, Siberia	130 yr	Ciavarella, et al. 2021
Jun 2021, North Western America	1000 yr	Philip et al., 2022
Mar-Apr 2022, India/Pakistan	100 yr	Zachariah et al., 2023a
Jul 2022, UK	100yr to 1000 yr	Zachariah et al 2022
Dec 2022, Argentina/Paraguay	20 yr	Rivera et al 2023
Apr 2023, Western Mediterranean	400yr	Philip et al., 2023
Apr 2023, South-East Asia and India	200yr and 5 yr	Zachariah et al., 2023b
Jul 2023, several regions of the world	5-15yr	Zachariah et al 2023c
Sep 2023, South America	30yr	Kew et al, 2023
Oct 2023, Madagascar	100yr	Pinto et al., 2023

These facts raise a number of questions. (i) Is there a temporal or regional bias or trend in the selection of events? (ii) Is the attribution method used, which relies on fairly strong assumptions, correctly estimating return periods, and in consequence the change in probabilities from preindustrial to current climate? (iii) Could there have been a nonlinear or abrupt change, or an acceleration in the change in intensity of

heat events, or an increase in variability that would result from a change in physical mechanisms? This article attempts to answer those questions with a systematic exploration of intense heat events, with estimated return periods from 10 years to 200 years, over the globe and over the 1979-2023 period. The systematic aspect of the analysis removes potential biases of type (i). As an analysis methodology, we used aggregated reliability statistics as in probabilistic weather forecasts (Palmer et al. 2004). To test (ii) and (iii), we used the now classical methodology of Generalised Extreme Value (GEV) with a location parameter linearly shifting with a global warming index as covariate such as described in (Philip et al., 2020) and assess the consistency of results. The principle of testing (ii) is simple: if the method and its underlying assumptions are valid, the frequency of occurrence of heat events with return periods estimated larger than N years should be $1/N$ (in which case, the model is considered to be well calibrated, together with its underlying assumptions). To test (iii), if there is an acceleration or nonlinear change of intensities worldwide or over specific regions, this frequency should exhibit a significant change with time or display a nonlinear time pattern. If there is no acceleration or nonlinear change, one expects heat extremes statistics to be essentially driven by the shift of mean values, such as suggested by multi-model analysis (van der Wiel and Bintanja, 2021).

Section 2 describes the data and the methods used. Section 3 the results and Section 4 includes a conclusion and a short discussion.

2. Data and Methods

We used two global gridded datasets and focus on daily mean temperature. The first dataset is the ERA5 reanalysis (Hersbasch et al., 2020) (1950-2023), and the second dataset is the observation-based CPC dataset, available over 1979-2023, (<https://psl.noaa.gov/data/gridded/data.cpc.globaltemp.html>). Both datasets were taken from the Climate Explorer (<https://climexp.knmi.nl>) where they are available at $0.5^\circ \times 0.5^\circ$ resolution globally. The CPC dataset describes daily maximum and minimum temperatures over land, which were averaged to estimate daily mean temperatures. Then, to save computing time, both datasets were reduced in spatial resolution, by averaging data over 8×8 cell blocks after removing non-land points (average land fraction larger than 0.5), hence describing temperatures at a spatial resolution of $4^\circ \times 4^\circ$. Extreme heat events tend to arise from large-scale circulation patterns covering areas larger than this resolution, so we expect not to remove much information with this spatial averaging. This results in 1357 grid points for ERA5 and 1071 for CPC. The main difference between the two

masks is that, unlike for ERA5, Antarctica is absent from CPC, as well as a few other regions. We restrict the analysis to latitudes above 65° S in order to have comparable results, reducing the number of grid points to 942.

We focus on the highest mean daily temperature of each year (denoted in the following as “TGx”) at each grid point, and use an Generalised Extreme Value (GEV) distribution for block maxima to model the data at each grid cell. For each year and each grid cell, the TGx data series is then modelled, as in heat event attribution, with a GEV fit of which parameters vary with a covariate representing the global warming defined as the 4-year running mean smoothed Global Mean Surface Temperatures (SGMST) from the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Science (GISS) surface temperature analysis (GISTEMP, Hansen et al., 2010 and Lenssen et al. 2019). Model parameters are estimated using maximum likelihood estimation, applied independently at each grid cell. In sensitivity experiments, we also used the smoothed ERA5 Global Surface Air Temperature (SGSAT). A main assumption is made that only the location parameter of the GEV distribution is changing, with a shift as a function of smoothed global temperature. This means an assumption that the intensity of events gradually shifts with global warming, without change in variability. This is an assumption that we want to test in this article and that is generally supported by models (van der Wiel and Bintanja, 2021).

We use, as a basis for all comparisons, the 1979-2023 period. For ERA5, we then obtain $45(\text{year}) \times 942(\text{grid cells}) \sim 42000$ estimations of return periods, and ~ 50000 for CPC, the difference originating from the difference in the number of land grid cells. We focus on high-magnitude events, with return periods larger or equal than 10 years, and up to 200 years. Sensitivity experiments are carried out also with ERA5 data taken from 1950-2023.

Other sensitivity experiments are designed to assess the near-real-time (NRT) approach, where data beyond the year of the event are not known, and therefore used. In the early attribution studies of WWA, the year of the event itself was removed to avoid a selection bias. We then compare the results for all these training time periods.

3. Results

We first evaluate the reliability of the GEV-covariate methodology using global statistics of the observed events associated with estimated RPs. This evaluation is based on the principle that the actual frequency of an event with estimated probability p should be precisely equal to p . When

annual events are defined in terms of the exceedance of a threshold T_0 (event: TT_0), with an estimated probability p in the climate of the warming level of the event year (using the GEV-covariate fit), one expects that the observed proportion of all events that exceed T_0 is p . In terms of return periods of yearly events, it means that for a given value of the RP, $RP=RP_0$, the expected observed frequency of events with estimated $RP>RP_0$ is $1/RP_0$, for all grid points. For rare events, the verification can benefit from a pooling of all grid-cells statistics.

Figure 1 shows the actual return period, calculated as the inverse of the proportion of events with estimated RPs larger than 10, 20, 50, 100 and 200 years (pooling the whole time series at all land grid points), as a function of these values. We find that the actual RP is very close to the estimated RP, with no indication of any nonlinearity in the relationship between the two, except when only 45 years of data is used to evaluate the most extreme events ($RP = 200$, red and black points). This demonstrates the validity of the assumption of a simple shift of the location parameter with global warming over the experimental period. Results depend weakly on the covariate dataset used (ERA5 or GISTEMP, see Fig. 1). We note however an overestimation of the estimated RP compared to the actual RP, which becomes significant when return periods greater than 50 years are considered: this is probably partly due to estimation of return periods higher than the length of the time series, and partly due to the known tendency of maximum likelihood estimation to overestimate return times (Zeder et al., 2023). We found that from 1950-1979 (prior to the satellite era), in some regions with few observation data (parts of South America and Africa), a large number of extreme events with high RPs was found (see also Figure 2). This makes the fit less appropriate, and explains why the 1979-2023 results show weaker departures. However an overestimation of about 20-25% remains, even for the 1979-2023 analysis for 50-year and 100-year events (ie. 50-year events found more frequently than expected, about 0.025% of the time). This could be due to variability and our assumption that years are independent from one another in the calculation of the confidence interval.

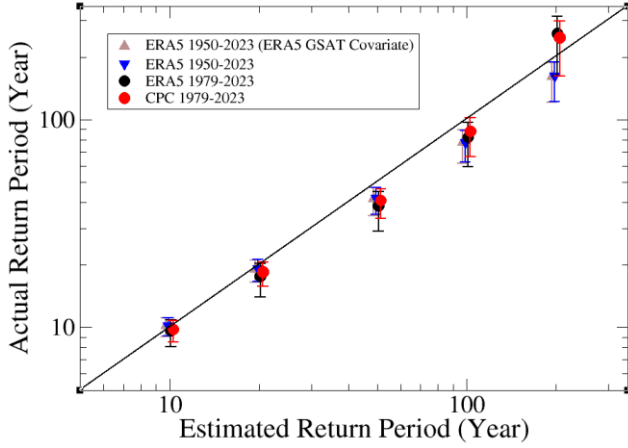


Figure 1: Actual return period (inverse of the observed proportion) of an estimated x -Year event, obtained by counting the number of occurrences of calculated return period greater than x , as a function of x (Year), across the dataset and across the global $4\times 4^\circ$ grid (over land). For each grid point and each year, the calculation of the return period follows the Generalised Extreme Value with a smoothed global temperature covariate developed as in Philip et al. (2021) and subsequent attribution studies. The mean over all grid points is shown with a point, while the 95% confidence interval (lines) is calculated as plus or minus two standard deviations of the yearly global proportion of events, divided by the square root of the number of years (minus 2), and then inverted to translate it into return period. Different colours and symbols represent different data sets or time periods used. Brown triangle stands for ERA5 with evaluation made over 1950-2023 using the smoothed covariate taken from the ERA5 reanalysis itself.

We then evaluate whether particular time patterns or trends are present in the frequency of high-amplitude events. Figure 2 shows the frequency, for each year, of 50-year events relative to the event's warming level of that year. Similar patterns are found for 10-year and 100-year events, with statistics done on land points over the whole global grid or rectangles encompassing each continent. A large year-to-year variability is found, reflecting the large spatial extent of extreme heat events. However, no statistically significant linear trend is found when considering the 1979-2023 period in any case. A slightly decreasing significant trend is found when using ERA5 starting in 1950, for the global grid, for Africa and South America. These trends are due to a large number of high-amplitude events in the beginning of the record: however, it is unclear whether this is a genuine phenomenon or an artefact of the reanalysis model in these regions. For example, Kew et al. (2023) decided to only use data from 1970 onwards in analysing a 10-day heatwave over southern Brazil and Paraguay, because there is no known reason why the variability could be so much larger between 1950-1970 than after 1970. This high variability could be

attributed to the limited historical synoptic observations within these regions, as highlighted in Bell et al. 2021. Differences between datasets can be large also in South America and Africa, but tend to be smaller in areas with more observation spatial coverage.

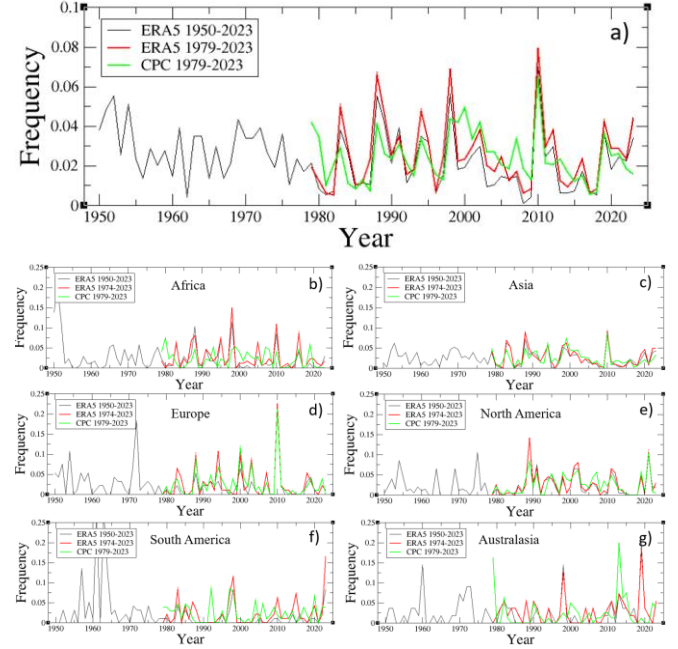


Figure 2: Time series representing the yearly spatial frequency (proportion of grid cells) of observed events over land with an estimated 50-year or more RP for TGx globally (a) and over rectangles encompassing each continent for CPC and ERA5. The bounds taken are as: Global) $[-180^\circ, 180^\circ, -65^\circ, 90^\circ]$; Africa) $[-20^\circ, 50^\circ; -40^\circ, 35^\circ]$ (b) ; Asia) $[50^\circ, 195^\circ; 0^\circ, 75^\circ]$ (c) ; Europe) $[-30^\circ, 50^\circ; 35^\circ, 75^\circ]$ (d) ; North America) $[-195^\circ, -50^\circ; 15^\circ, 75^\circ]$ (e) ; South America) $[-90^\circ, -30^\circ; -60^\circ, 15^\circ]$ (f) ; Australasia) $[90^\circ, 180^\circ; -50^\circ, 20^\circ]$ (g).

There are specific years characterised by a high proportion of grid points with extreme heat events, such as 2010 for Europe and Asia, 1989 for North America, and 2023 for South America. In the first case, this is due to the Russian heatwave, with outstanding values over a large area (Barriopedro et al., 2011). In the second case, a large area of the Northern parts of North America was affected by anomalous heat. For South America, spring and early summer 2023 had outstanding temperatures in several regions, as well as the end of the previous summer (Arias et al., 2023; Kew et al., 2023). Interestingly, recent El Niño years do not stick out with a large frequency of high-amplitude events at global scale.

In 2023, high-amplitude heat events were frequent, but the proportion of grid cells relative to current warming level was not a record in any region except in South America. A

proportion of 2-5% of grid points witnessed at least 50-year events (depending on dataset). This is much less than than the fraction obtained in other specific years (eg. 2010). We conclude that the frequency of high-amplitude heat events in 2023 was not exceptional when considering the overall climate change trend.

Figure 3 shows the trends in the proportion of grid cells exceeding the temperature corresponding to the RP in the climate of 2000 (thick lines) vs. the RP in a warming climate (thin lines); trends are shown for return periods of 10 years (black lines) and 50 years (red lines). Considering the thin lines representing exceedances in a warming climate, we see no evidence of any trend: the black lines vary around 0.1 and the red around 0.02, as we would expect if the linear warming trend fits the data well. However, exceedances of what would have been 1-in-10-year and 1-in-50-year events in the climate of 2000 have increased dramatically in the last two decades, and actually over time, with an exponential growth. The exponential fits give a doubling time of about 9 years for 50-year events and 14 years for 10-year events. Relative to its own warming level (thin lines), the spatial extent of exceedances in 2023 was not particularly unusual, but such widespread high temperatures would have been absolutely exceptional at a warming level equivalent to that of 2000 (about 0.5°C less than in 2023). Overall the frequency of extreme heat events, taken in the 2000 warming context, have seen their frequencies quadruple in the last two decades.

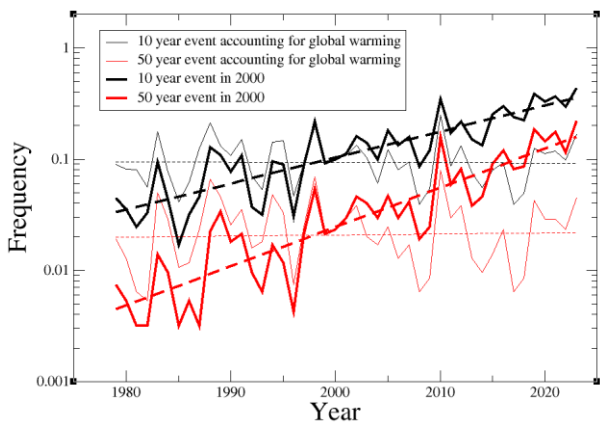


Figure 3: Time series of annual spatial frequency of events with an estimated 10-year RP (black) and 50-year RP (red) using a GEV with variable global warming covariate (thin lines) or assuming a fixed covariate as the warming level of 2000 (thick lines). Trend lines (dashed lines) are estimated using an exponential trend assumption.

Our results also show the consistency of the GEV-covariate methodology used in WWA event attribution studies done in recent years (see Table 1). However, in early studies (eg. until 2022), the assumption was made that

including the value of the event under analysis would induce some “selection bias”, artificially inflating the probability of the event, if done systematically in real time attribution studies. However, it has been shown that excluding the event itself also creates such a bias (Miralles and Davidson, 2023). Figure 4 shows that the bias arising from excluding the event tends to be larger than the bias arising from including it, with the bias in both cases increasing for more extreme events. The explanation is simple: for events with RPs lower than the sample length, the probability is usually estimated correctly because several such events are present in the record. For events with RPs of the order of the sample length or higher, which are often record-breaking events, a single realisation adds crucial information: this makes the GEV fit very sensitive. Figure 4 shows that the bias in the estimation of the PR can be as large as a factor of two for 50-year or more events.

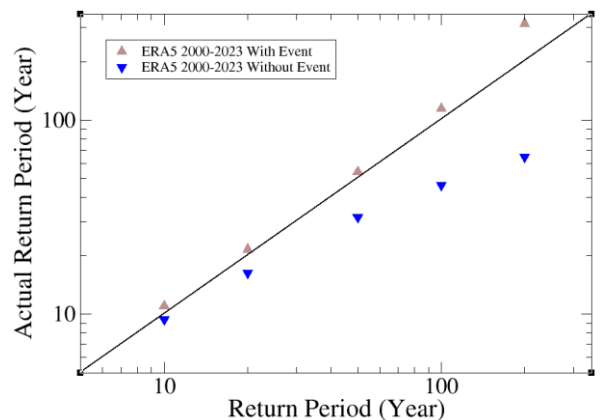


Figure 4: Same as Figure 1 but using the operational real-time method of Philip et al. (2021), including (brown) or not (blue) the event itself, and removing data posterior to the event year, as done in real-time World Weather Attribution analyses.

Another question is whether the assumption of linearity and constant variance remains valid in future scenarios with higher warming levels. WWA studies generally extend the analysis to projections of the current event in a “2°C warmer climate”, by extending, for climate models only, the training period for the GEV fit up to 2050. A full multi-model ensemble analysis here would be too long to do, so we conducted a limited sensitivity analysis to potential extension of our results into higher warming levels. We selected 3 different models, with contrasted climate sensitivities from the CMIP6 experiment, and a single realisation (the first one of each ensemble) of the historical period, completed with the SSP5-8.5 scenario: ACCESS-ESM1-5 (3.4°C warming level in 2050), IPSL-CM6-A-LR (2.9°C warming level in 2050) and MPI-ESM1-2-LR (2.0°C warming level in 2050). In each case, the same statistical analysis was carried out as above out over land grid points (as defined from the model’s

land-sea mask and aggregating to a grid with about a $4^{\circ} \times 4^{\circ}$ resolution), with the analysis over the period 1979-2050 instead of 1979-2023. Figure 5 shows the resulting time series for the frequency of 50-year events along the period, showing here a similar variability as in Figure 2a and an absence of trend or low-frequency variability, as well as no apparent change in variability. This indicates that up to about a 2°C warming at least the “shifting assumption” remains valid, justifying its use in WWA studies. More multi-model/multi-member experiments could however quantitatively assess these latter points, which can be left for future analyses.

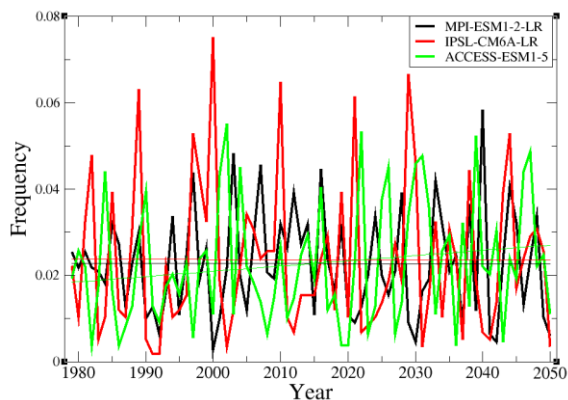


Figure 5: as in Figure 2 for the global statistics of yearly maximum of daily temperature 50-year events, using the 1979-2050 period and the historical and SSP5-8.5 scenario for three CMIP6 models (see legend) with contrasted warming in 2050.

4. Conclusion and discussion

Our results first show that there is consistency between the observed frequency of high-amplitude heat extremes worldwide and their estimated return periods (RPs) as estimated using a GEV with the assumptions of a location parameter shifting with global warming. Firstly, this provides some confidence in the assumption of a GEV distribution with a global warming covariate for the location parameter only. Our results also show that the frequency of such extremes, when considered at the “warming level of the year of their occurrence”, are not exhibiting a trend, neither a nonlinear behaviour, nor an “acceleration” (a change of speed) as often interpreted in media reports. Instead, we show that the magnitude of exceptional events with eg. a frequency of 50-years at the beginning of the 21st century (2000) are now already becoming much less exceptional. Our results also show that despite a linear shift with global warming level, the frequency of high-amplitude heat extremes (highest daily temperature of the year) has been increasing exponentially globally with doubling times of about 9 years for 50-year events and 14 years for 10-year events.

This apparent paradox of a linear shift of frequency conditioned on the warming level at event year, and the exponentially increasing frequency when considering the reference of a fixed warming level can be explained by the rapid growth of probability in the shifting tail of distributions with external forcing, and not by an acceleration of global temperatures, which underwent a rather steady increase since 1979.

Overall, the rapid increase in heat extremes suggests that even the “climate of ten years ago” may not be a suitable reference for today’s climate regarding such extreme events. Because risks (eg. for health, agriculture) are particularly high for large heat anomalies, the so-rapid pace means that there is currently no observational reference for risks related to heat extremes. This provides a particularly strong motivation to understand the potential consequences of events of previously unseen amplitude or duration, in order to design scenarios for adaptation. This can be done through the design of specific “worst case” or stress tests studies for a given city or region, with implications for practitioners.

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Data availability statement

The data will be made publicly available upon publication, but are available from the authors upon request.

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