Climate change emergence over people's lifetimes

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Climate change emergence over people's lifetimes

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Abstract

The emergence of climate change from background variability is a useful metric for identifying changes in local climate which may affect people and ecosystems. Studies have found that equatorial regions, which are typically poorer, experience clearer climate change emergence over the observational record and in model projections. Here, we perform the first analysis of people's experienced climate change relative to background variability, and we examine where people have already lived through an emergence of local warming. We calculate signal-to-noise (S/N) ratios and combine these with demographic data to compute local emergence of warming over human lifetimes. Younger people have typically experienced less clear emergence of a climate change signal over their lifetimes to date. Over a given time period, tropical, lower-income areas have experienced higher S/N than extratropical and typically higher-income areas. However, this is counter-balanced by the younger populations of these areas such that the median experienced S/N ratio is similar between the wealthiest and poorest parts of the world. Given projected ageing of low-income regions, it is imperative that substantial climate action is taken to avoid local climates becoming unrecognizable within human lifetimes.

1. Introduction

Global and local temperatures have increased over the last century due to anthropogenic greenhouse gas emissions. The warming has been great enough over the instrumental period to have emerged from background variability even at local scales (Hawkins *et al* 2020). Emergence of local warming has been particularly clear in tropical regions where variability is lower than in mid-to-high latitude areas (Mahlstein *et al* 2011, 2012). Tropical areas tend to be poorer, which has led to the alarming conclusion that the regions that have contributed least to human-caused climate change, and typically also have the least resilience to climate change impacts, are the areas that have experienced and will continue to feel the clearest climate change effects on local temperatures (Harrington *et al* 2016, King and Harrington 2018, Frame *et al* 2019).

There have been several studies examining different aspects of the emergence of a climate change signal from background climate variability (Diffenbaugh and Scherer 2011, Hawkins and Sutton 2012, Lyu *et al* 2014, King *et al* 2015, Abatzoglou *et al* 2019, Abram *et al* 2021). The majority of analyses have focused on physical climate changes but there has been some consideration of emergence of climate change impacts on human population (Lehner and Stocker 2015, Frame *et al* 2017) and other species (Mora *et al* 2013, Henson *et al* 2017). Frame *et al* (2017) identified large benefits by the late 21st century from following a low rather than a high greenhouse gas emissions pathway with respect to climate change emergence effects on human population.

A significant gap remains, however, in investigating people's exposure to climate change emergence in their lifetimes to date. It is useful to understand who has experienced significant warming to date, particularly in the context of vulnerability. Identifying who has already experienced the emergence of significant warming during their lives may also help explain attitudes to anthropogenic climate change (Lehner and Stocker 2015) and its importance as a challenge facing civilization. There is some evidence that people's experience of local climate change contributes to their level of concern about the problem of global climate change (e.g. Broomell *et al* 2015, Sambrook *et al* 2021), noting that perception of climate change and physical experience of climate change over people's lifespans may well differ. In this study, we estimate the emergence of local warming signals that different people have experienced across the world.

2. Data and methods

Here we use gridded observational temperature, population demographics, and gross domestic product (GDP) estimates to examine emergence of climate change by age and income across the world. The computation of a quantitative metric that represents experience of climate changes by local populations is non-trivial. A variety of different methods have been used to compute climate change emergence including tests that compare statistical distributions (Mahlstein *et al* 2011, King *et al* 2015) and signal-to-noise (S/N) ratios (Frame *et al* 2017, Hawkins *et al* 2020). S/N ratios capture the magnitude of changes relative to variability while also providing flexibility with respect to sample size that is more challenging when using distribution comparison tests, such as the Kolmogorov–Smirnov test. We use S/N ratios, similar to calculations used in previous analyses (Frame *et al* 2017, Hawkins *et al* 2020), to quantify climate change emergence in annual-average temperatures.

The Berkeley Earth Surface Temperature (BEST; Rohde and Hausfather 2020) dataset was used to compute global annual-average and local annual-average temperatures over 1900–2021 inclusive. S/N ratios were computed by adapting the methodology of Hawkins *et al* (2020). Local temperature is regressed onto smoothed global mean surface temperature (GMST):

$$L(t_1) - L(t_0) = \alpha\,(G(t_1) - G(t_0)) + \beta\,(t_1) - \beta\,(t_0),$$

where $L(t_1){-}L(t_0)$ is local change in annual temperature between start date, t_0, and end date, t_1, $G(t_1){-}G(t_0)$ is unweighted 15-year smoothed GMST change over the same time period, α is the linear scaling between L and G over the time period and $\beta(t_1){-}\beta(t_0)$ is a constant. The key modification from the method of Hawkins *et al* (2020) is that this calculation is repeated with different start dates (t_0) and end dates (t_1) during the 1900–2021 observational period studied. The signal is defined as $\alpha(G(t_1){-}G(t_0))$ and the noise as the standard deviation of residuals, $L(t_1){-}L(t_0){-}\alpha(G(t_1)\text{-}G(t_0))$, such that signal and noise, and the S/N ratio are allowed to vary spatially and between age brackets and time periods. This marks a departure from previous studies (Frame *et al* 2017, Hawkins *et al* 2020) where a single noise estimate for a given location was often used. Given the purpose of this study to examine people's experiences of climate change over a given time period we chose to calculate noise to match people's experienced climate variability rather than computing noise from a climate outside their lifetimes. For most analysis conducted here, the end date, t_1, is 2021, but analysis of S/N ratios over time periods ending prior to 2021 was also conducted. Examples of temperature timeseries with computed S/N ratios over different time periods up to 2021 are shown in figure S1.

Socioeconomic data based on 2010 estimates were used due to data availability and relevance (see Discussion and Conclusions section for further information on the use of 2010 data and sensitivity tests partially using 2020 data). The populations exposed to varying degrees of warming were computed using 2010 population demographics data from the NASA Socioeconomic Data and Applications Center (Basic Demographic Characteristics, v4.11: Gridded Population of the World (GPW), v4 2018). Male and female population data were merged and 5-year age brackets were analyzed. While age brackets extend to children below 15 years of age, such short time periods are not long enough to compute robust S/N ratios and examine changes over lifetimes. As it is, S/N ratios over shorter time periods are more sensitive to natural interannual-to-interdecadal climate variability and the short-term effects of volcanic eruptions on the climate (Santer *et al* 2011). Also, we examine population experience of climate change only for people under 84 years of age, due to the availability of demographic data (Basic Demographic Characteristics, v4.11: Gridded Population of the World (GPW), v4 2018) up to that age. This means our analysis is based on a population of 4.95 billion people (or 71% of global population using 2010 estimates).

The distribution of S/N ratios experienced by the global population was examined by calculating S/N ratios at each gridbox for each age bracket. Signal and noise were computed across the globe for each lifespan to quantify both the warming and variability that that age group has experienced. The median S/N ratio as well as the fraction of population experiencing S/N ratios greater than different thresholds were computed. The distributions of S/N by age bracket across the globe were also analyzed.

GDP estimates for 2010 (Murakami and Yamagata 2016) were used in conjunction with the 2010 total population data (not only the 15–84-year old population used elsewhere) to compute gridded GDP per capita estimates. The global population was divided into approximately even income deciles (figure S2), and these were used to examine vulnerability under different S/N ratios. Median S/N ratios by income decile and age bracket, and the total population by age bracket within each income decile were computed. The distribution of S/N ratios experienced by the population within each income decile (accounting for their different demographics) was also calculated.

All analysis described above was conducted on a regular 1° grid. The GDP and total population data were aggregated onto a 1° grid, matching the temperature and population demographics data, before the GDP per capita estimates were computed. Sensitivity tests on the effect of regridding were conducted and are summarized in supplementary information.

3. Results

We estimate that the median S/N experienced across the global population of 15–84-year-olds up to 2021 is 1.99. This means just under 50% of the global population in that age range have experienced an S/N greater than 2 during their lifetimes. To adopt the wording of Frame *et al* (2017), this is equivalent to almost half of the world's 15–84-year-old population now experiencing an 'unfamiliar' climate relative to when they were born. We find that fewer than 1% of the global population of 15–84-year-olds have experienced S/N > 3, a transition to an 'unknown' climate, but 89% have experienced S/N > 1 which represents a change to an 'unusual' climate. Only 3% of the world's population of 15–84-year-olds have experienced S/N ratios below zero in their lifetimes. Negative S/N occurs where there is local cooling over one or two decades, caused by a combination of natural variability, land use change, and changes to emissions of short-lived forcing agents like aerosols.

S/N ratios vary across the world and also for people of different ages (figure 1). S/N is more spatially variable over shorter timeframes (figure 1(c)), so younger people's experience of warming differs strongly by location. For middle-aged people or older populations, S/N ratios are more spatially homogeneous and generally higher (figures 1(a) and (b)). Consistent with previous studies (Mahlstein *et al* 2011, 2012, Harrington *et al* 2016, King and Harrington 2018, Hawkins *et al* 2020), S/N is typically higher in low-latitude locations than in the extratropics over longer time periods. Particularly high S/N ratios are identified in Sub-Saharan Africa and the Maritime Continent. The populated location (greater than 100 000 inhabitants in the gridcell) with the highest S/N ratio for any age bracket is at 32° N, 23° E which includes the city of Benghazi, Libya. People at this location who are 50 years old have experienced an S/N of 3.05 during their lives up to 2021.

Globally, middle-aged people tend to have experienced more significant local warming than people over 70 years old (figure 1). This is due to the lack of warming globally, and cooling in many populated locations, from the 1940s to the 1970s. This cooling was primarily driven by anthropogenic aerosol emissions (Booth *et al* 2012) and this has the effect of reducing the climate change signal over many people's lifetimes who were born before 1960. It may seem counter-intuitive that longer periods are not always associated with greater S/N ratios, but early times of cooling or lack of warming reduce the detectability of the climate change signal when considering full lifetimes. This is seen at many locations including the gridcells over New York, Kinshasa and Delhi as shown in figures S1(a)–(c).

By calculating S/N ratios for different periods finishing prior to 2021 we observe that the middle-aged and older people of today have experienced more significant local warming than people of the same ages did in the past (figures 1 and S3). For younger people there is more variability as decadal-scale periods of accelerated or slowed warming (Maher *et al* 2014) greatly influence local S/N ratios over shorter windows of time (figures S3 and S4). There is likely signal contamination by noise on shorter timescales in the calculations performed here, but we can also compare the signal and noise estimates separately for different time periods to identify which part of the S/N ratio is causing differences between age brackets. Variability in the signal estimate between age brackets influences S/N ratios while variability in the noise estimate by age bracket is small (figures S5 and S6). Changes in noise estimates are strongest in less populated areas, including in regions with seasonal ice cover where decreases in ice coverage have resulted in increased interannual variability more recently (figure S6).

While S/N ratios are higher over given time periods in the tropics than at higher latitudes, differences in demographics also affect the emergence of local climate changes experienced by populations. If we examine S/N ratios by income decile and age bracket (figure 2(a)) then we find that older people (over 70-years old) in

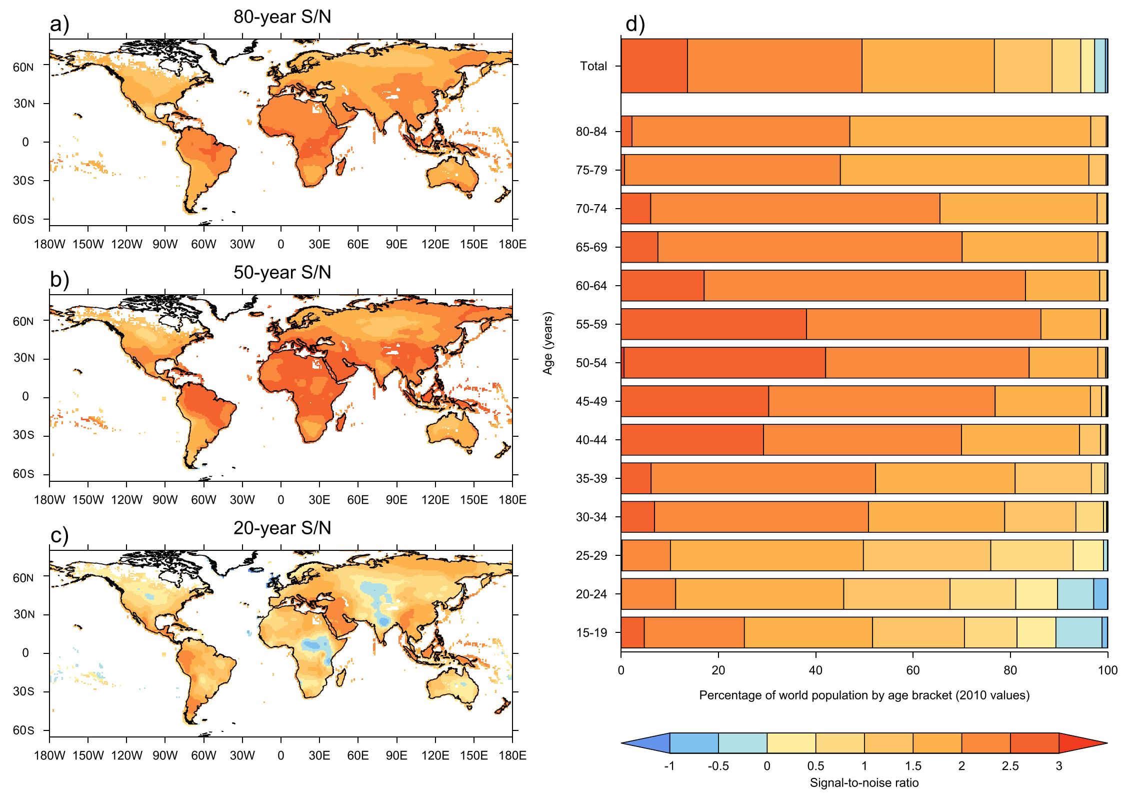

Figure 1. Clearer climate change emergence for middle-aged people. Maps of signal-to-noise ratios in annual temperature for (a) 80 years, (b) 50 years, and (c) 20 years up to 2021. S/N ratios are plotted at inhabited locations only. (d) Percentage of global population, for the entire 15–84-year-old population and by 5-year age bracket, who have experienced different S/N ratios to 2021.

low-income areas have experienced more significant local temperature changes than older people in medium and high-income places. The lowest income decile locations are predominantly in Sub-Saharan Africa (figure S2) which coincides with where the highest S/N ratios over periods of more than 60 years are found. In middle-income areas, including much of eastern China, for example, and in the lowest income decile areas, middle-aged people have experienced more significant warming than people of the same age in other parts of the world. For younger people, the S/N ratios tend to be lower and the relationship with income is more variable between age bands.

The demographics of population by income decile vary greatly, with low-income countries characterized by far younger populations than either middle-income or wealthy parts of the world (figure 2(b)). Even though S/N ratios are typically higher over a given period of time in low-income areas relative to high-income areas, the youthful population of low-income places means that the climate change emergence experienced by the average person in each income decile is not very different (figure 2(c)). In fact, it is only in the middle-income countries where most people experience clearer emergence of warming than the global average.

The median S/N experienced by the 15–84-year-old population is positive at all locations but is particularly high across heavily-populated middle-income areas such as China (figure 3(a)). The distribution of S/N ratios is broader for people in low-income than high-income regions due to the greater variability of S/N experienced between people over shorter lifetimes and between locations (figure 2(c)). In areas of sub-Saharan Africa and northern India which sit in the lower income deciles, younger people have experienced cooling (figures 1 and 3(b)). In contrast, the 25th percentile of S/N ratio across the 15–84-year-old population is above two across much of China and Southeast Asia. The 75th percentile S/N ratio is also particularly high in east and Southeast Asia as well as in southern Europe (figure 3(c)).

The income deciles each cover a large population (approximately 500 million people aged 15–84 for whom S/N ratios are estimated) such that large city locations do not dominate the results. Median S/N ratios experienced by people in the world's largest cities vary substantially and without a strong relationship with income decile (table S1). Delhi has experienced a moderate cooling trend in recent decades (figure 1(c)) reducing the median S/N ratio (figure 3(a)) experienced well below that in other very large cities.

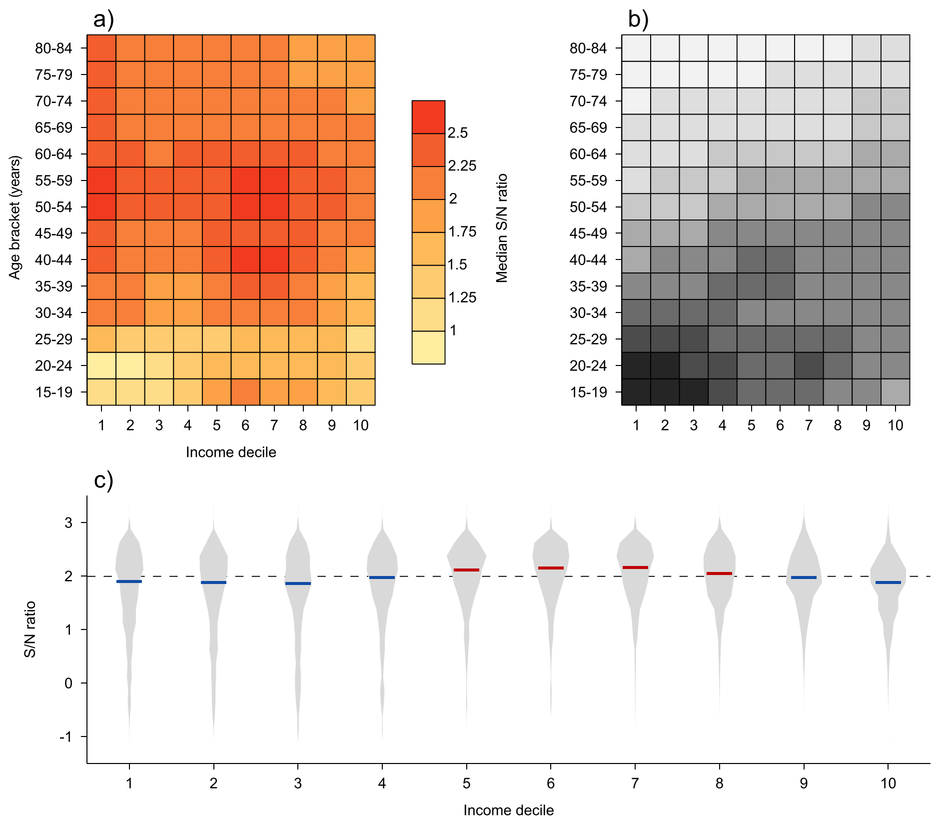

Figure 2. Younger populations in the developing world counterbalance higher signal-to-noise ratios over climatological periods. Grids of (a) median signal-to-noise ratios to 2021 and (b) population by income decile and age bracket. (c) Violin plots showing the distribution of signal-to-noise ratios experienced by the population of each income decile up to 2021. Horizontal lines mark the medians and are colored red where they are above the global population median S/N ratio and blue when below the global median. The dashed line marks the global median.

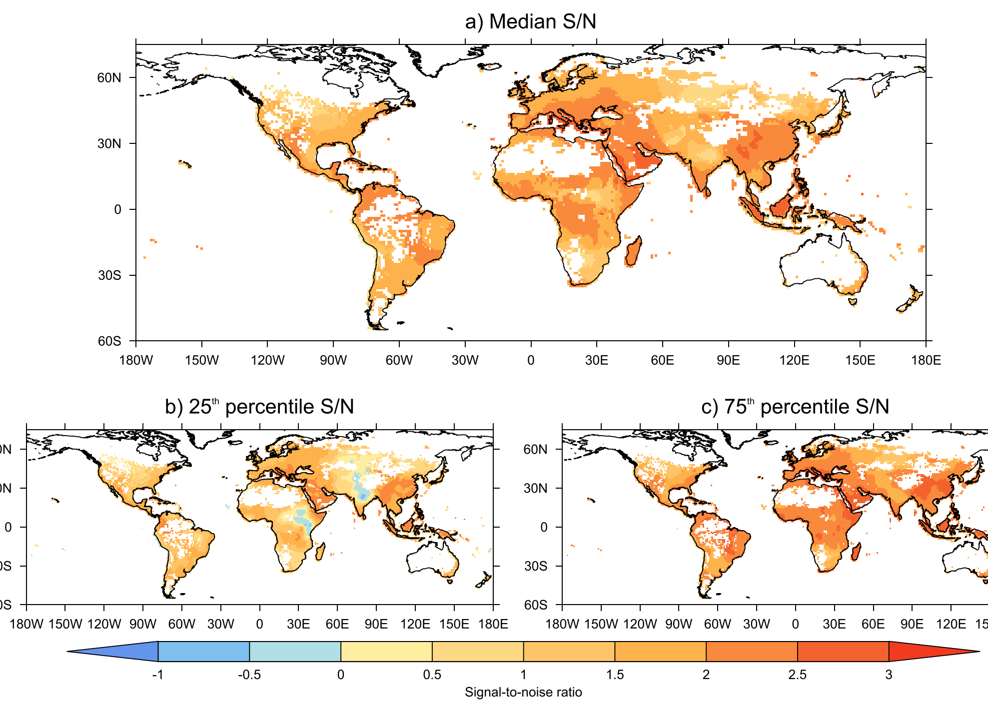

Figure 3. Distribution of signal-to-noise ratios experienced by population across age brackets at each location. The (a) median, (b) 25th percentile, and (c) 75th percentile S/N ratio to 2021 across the population at each location. S/N ratios are shown for gridcells with at least 10 000 inhabitants only.

4. Discussion and conclusions

Climate change emergence studies have been performed due to the usefulness of emergence as an indicator of climate change which accounts for variability as well as trends. The concept of climate emergence is relevant to ecological systems and individual species, and also to human experiences of climate change. There is growing interest in relating climate change to people's experiences as illustrated by the inclusion of lifespans in a key figure (Figure SPM.1) of the Synthesis Report of the Intergovernmental Panel on Climate Change Sixth Assessment Report (IPCC AR6, Lee *et al* 2023). Here, we examine people's experiences of local temperature changes as the world has warmed.

This is the first analysis that attempts to estimate the emergence of local climate change signals experienced by the population of the world, young and old, rich and poor. We demonstrate that while low-income areas, predominantly in the tropics, have experienced more significant warming over long time windows, the relatively young populations of these areas result in less clear local warming than has generally been experienced by populations of middle-income places.

Several methodological choices were made during this study, so sensitivity tests were performed (supplementary information) and there are a number of caveats that should be noted. This study uses climate (Rohde and Hausfather 2020) and socioeconomic (Murakami and Yamagata 2016, Basic Demographic Characteristics, v4.11: Gridded Population of the World (GPW), v4 2018) data to explore climate changes and the associated exposure and vulnerability of populations. As with any such study there are potential issues with data quality. Most of the analysis involves aggregating information from individual gridcells which reduces the effect of possible localized data quality issues. The city-scale results highlighted in table S1 are inherently more uncertain than the global, age-bracket or income decile aggregated results.

The socioeconomic data used are based on 2010 estimates as the population demographics information is only available for that time (Basic Demographic Characteristics, v4.11: Gridded Population of the World (GPW), v4 2018). Analysis based on GDP per capita estimates for 2020 in combination with the demographics data from 2010 shows broadly similar results (figures S7 and S8). Using 2020 GDP per capita estimates leads to increases in S/N ratios in the eighth income decile as parts of China rise into this wealth bracket. We use 2010 data only for the main results shown for consistency across datasets, but we primarily frame results around the percentage of global population rather than using raw numbers in recognition of the global population growth since 2010. For the analysis of population exposure through time the effects of demographic changes are likely to be larger, so this analysis should be treated with caution as we note in the caption to figure S3.

The use of S/N ratios as a measure of experienced climate change is consistent with choices from previous literature (e.g. Frame *et al* 2017, Hawkins *et al* 2020). For the purposes of understanding perceptibility of climate change, a metric which placed more weight on recent changes might align better with human perception as experienced by real people. However, determining this weighting in a robust way would require reliable insight into human cognition across all cultures and age groups, and so this was deemed to be impractical. We make a deliberate choice in this study to focus on a physical measure of experienced climate change rather than an inherently more subjective measure of perceptible climate change.

This analysis is based on an assumption of populations remaining at a given location through time. Of course, populations are mobile, in some regions more than others (Kraemer *et al* 2020), albeit more for short-term than long-term travel. In total, only around 3%–4% of the global population are international migrants (United Nations 2020).

This study adds important detail to previous findings on the earlier and stronger low-latitude emergence of warming and associated inequality with this pattern. It is worth remarking on the finding that the average S/N ratio experienced by people in low and high-income areas is similar, despite the much older population in the top income deciles. This suggests that as the poorest areas of the world develop and the population ages, the climate changes experienced over people's lifespans may worsen, unless there is a substantial slowdown in the rate of global warming. If greenhouse gas emissions rapidly fall, to support meeting the Paris Agreement goals of limiting global warming to low levels (Meinshausen *et al* 2022), then many young people in lower income countries could avoid unrecognizable changes in their local climate later in life.

Data availability statement

The BEST dataset was used. GMST data and gridded monthly land and ocean data were downloaded from http://berkeleyearth.org/data/. Population demographics (2010 estimates) were downloaded from the NASA Socioeconomic Data and Applications Center (https://sedac.ciesin.columbia.edu/data/set/gpw-v4-basic-demographic-characteristics-rev11/data-download) at 1° resolution. Gross domestic product (GDP) per capita estimates for 2010 were calculated from GDP and total population estimates for 2010 downloaded from https://warp.da.ndl.go.jp/info:ndljp/pid/12232413/cger.nies.go.jp/gcp/population-and-gdp.html. All code used in this analysis is available from https://doi.org/10.5281/zenodo.7006834.

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Conflict of interest

The authors declare no competing interests.

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