POLICY FORUM

CLIMATE CHANGE

Intergenerational inequities in exposure to climate extremes

Young generations are severely threatened by climate change

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Under continued global warming, extreme events such as heat waves will continue to rise in frequency, intensity, duration, and spatial extent over the next decades (*1*–*4*). Younger generations are therefore expected to face more such events across their lifetimes compared with older generations. This raises important issues of solidarity and fairness across generations (*5*, *6*) that have fueled a surge of climate protests led by young people in recent years and that underpin issues of intergenerational equity raised in recent climate litigation. However, the standard scientific paradigm is to assess climate change in discrete time windows or at discrete levels of warming (*7*), a "period" approach that inhibits quantification of how much more extreme events a particular generation will experience over its lifetime compared with another. By developing a "cohort" perspective to quantify changes in lifetime exposure to climate extremes and compare across generations (see the first figure), we estimate that children born in 2020 will experience a two- to sevenfold increase in extreme events, particularly heat waves, compared with people born in 1960, under current climate policy pledges. Our results highlight a severe threat to the safety of young generations and call for drastic emission reductions to safeguard their future.

Meteorological extremes, hazards, or climate change impacts are mostly studied as they evolve over time under varying emission scenarios and socioeconomic pathways (*2*, *4*, *8*). For example, applying a heat wave indicator (see table S1) (*9*) to four bias-adjusted global climate models indicates that the land area annually affected by such heat waves will increase from ~15% around 2020 to ~22% by 2100 under a scenario compatible with limiting global warming to 1.5°C, and to ~46% under a scenario in line with current emission reduction pledges (see the first figure). Recent studies extended this approach, studying aspects of climate change as a function of global mean temperature (GMT) increments, highlighting the scenario-independence of several extreme event indicators (*1*, *3*, *8*) but remaining, in essence, a comparison of time windows.

By contrast, we performed a birth cohort analysis by combining a collection of multimodel extreme event projections (*3*) with country-scale life expectancy information (*10*), gridded population data (*11*), and future global temperature trajectories (*12*) from the Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5°C (see supplementary materials). By integrating the exposure of an average person in a country or region to extreme events across their lifetime, we encapsulate spatiotemporal changes in climate hazards, population density, cohort size, and life expectancy (see the first figure).

EXTREME EVENT EXPOSURE

Our results allow for comparing lifetime exposure to climate extremes across birth cohorts globally. For example, a person born in 1960 will on average experience around 4 ± 2 (1σ) heat waves across their lifetime according to our extreme heat wave definition (see the first figure). The lifetime heat wave exposure of this cohort is largely insensitive to the three future temperature scenarios considered here. By contrast, a child born in 2020 will experience 30 ± 9 heat waves under a scenario that follows current climate pledges, which could be reduced to 22 ± 7 heat waves if warming is limited to 2°C or 18 ± 8 heat waves if it is limited to 1.5°C. In any case, that is seven, six, or four times more, respectively, compared with that of a person born in 1960. Repeating this analysis for all cohorts born between 1960 and 2020 highlights clear differences in lifetime exposure to heat waves between older and younger cohorts globally (see the first figure). The effect of alternative future temperature trajectories on the lifetime exposure multiplication factor becomes discernible only for cohorts younger than 40 years in 2020, with the largest differences for the youngest cohorts.

The previous example only uses one hazard indicator and a subset of all possible future temperature pathways. We expanded this approach and considered six extreme event categories: wildfires, crop failures, droughts, river floods, heat waves, and tropical cyclones (see table S1), which we analyzed under a wide range of temperature pathways that resulted in future warming that ranges from constant present-day levels up to 3.5°C by 2100 (see materials and methods and fig. S1). To this end, we generated a total of 273 global-scale projections with 15 impact models forced by four bias-adjusted global climate models (see table S2). Inspired by the IPCC's Reasons for Concern Framework (*7*), we visualized the exposure multiplication factors, relative to a hypothetical reference person living under preindustrial climate conditions, as a function of the 2100 GMT anomaly and cohort (see the second figure and fig. S2). Life expectancy varies with the cohort, whereas the hypothetical reference person is given the same life expectancy as that of the 1960 birth cohort in our figures. Therefore, in contrast to the previous comparison of lifetime exposure across generations given historical and climate conditions (see the first figure), we assessed how projected lifetime exposure of birth cohorts is affected by climate change since the preindustrial era and by increased life expectancy since 1960.

Our results highlight that lifetime exposure to each of the considered extreme events consistently increases for higher warming levels and younger cohorts. Changes in extreme event frequencies have relatively little effect on lifetime exposure for cohorts above age 55 in 2020, but this rapidly changes for younger cohorts as they experience increasing extreme events in the coming years and decades (see the second figure and fig. S2). For a 3°C global warming pathway, a 6-year-old in 2020 will experience twice as many wildfires and tropical cyclones, three times more river floods, four times more crop failures, five times more droughts, and 36 times more

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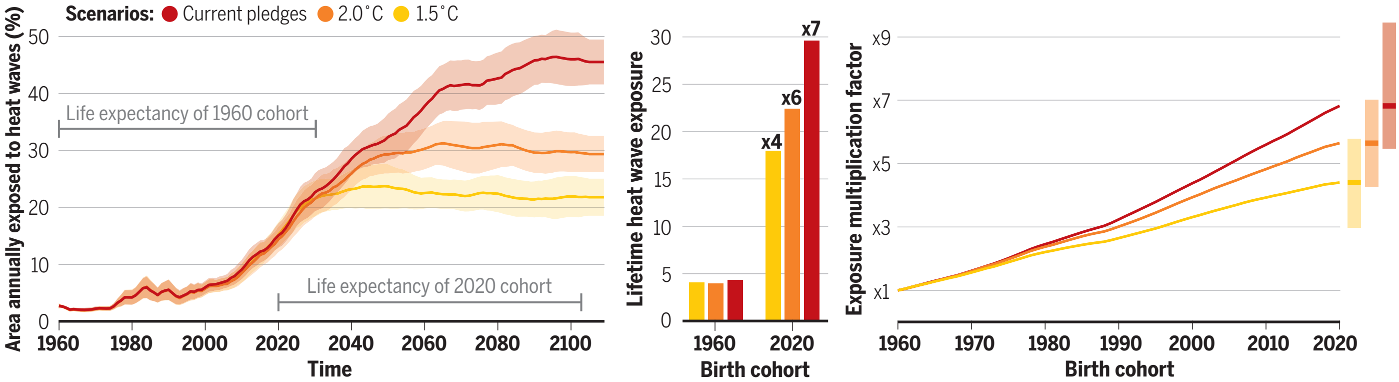
From a period to a cohort perspective on extreme event exposure

(Left) Global land area annually exposed to heat waves under three scenarios is shown. Lines represent multimodel means of a heat wave metric calculated from four global climate models. Lines were smoothed by using a 10-point moving average. Uncertainty bands span 1 standard deviation across the model ensemble. (Middle) Lifetime heat wave exposure for the 1960 and 2020 birth cohorts under the three scenarios is shown. Numbers above bars indicate exposure multiplication factors relative to the 1960 cohort. (Right) Shown are multiplication factors for lifetime heat wave exposure across birth cohorts relative to the 1960 cohort. Uncertainty bands represent the interquartile range for the 2020 cohort exposure relative to the multi-model mean exposure of the 1960 cohort.



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heat waves relative to the reference person.

Although qualitatively consistent, quantitative exposure changes differ among categories: For wildfires and tropical cyclones, increases in exposure remain limited relative to the other categories, whereas heat wave exposure increases much more strongly, up to a factor of 44 for the 2020 birth cohort under a scenario with 3.5°C global warming. Aggregating the exposure multiplication factors across the six categories shows that people younger than 10 years in 2020 will experience about a fourfold increase in extreme events if global warming is limited to 1.5°C, an increase that older cohorts will never experience, even if a scenario toward 3.5°C warming is followed (see fig. S3A). Under a 3°C global warming pathway, children under 8 years will face an almost fivefold increase in extreme event exposure. These exposure multiplication factors scale robustly with the warming pathway and cohort across a range of aggregation methods, despite some variation in the factor values (see fig. S3).

We then calculated the probability of each person's lifetime exposure occurring under preindustrial climate conditions. Lives with an accumulated exposure that would occur with less than 0.01% probability under preindustrial climate (that is, with less than a 1 in 10,000 chance) are classified as "unprecedented." We found that cohorts above age 55 years in 2020 will on average live an unprecedented life only for heat waves and crop failures, whereas cohorts aged 0 to 40 years in 2020 will additionally face unprecedented exposure to droughts and flooding above 1.5°C warming (see the second figure). Aggregated across all the event categories, lifetime exposure to extremes is unprecedented at all warming levels and cohorts (see fig. S3A).

REGIONAL PATTERNS

Behind this global average picture, there are important spatial variations. Repeating the analysis for a selection of world regions (see fig. S4) reveals marked differences between regions (see figs. S5 and S6), whereas a country-level assessment highlights even stronger spatial disparities (see supplementary text 1 and figs. S7 and S8). We found a particularly strong increase in lifetime exposure across the Middle East and North Africa, with on average at least seven times higher exposure for all cohorts younger than 25 years in 2020 under current emission reduction pledges (see fig. S9A). In sub-Saharan Africa, the 2020 birth cohort will on average experience 5.9 times more extreme events compared with a reference person living under preindustrial climate, whereas in other regions this cohort will on average experience 3.7 to 5.3 times more extremes. This burden is substantially reduced when limiting global warming to 1.5°C: the strongest reductions in exposure are found in the Middle East and North Africa (–39%), Europe and Central Asia (–28%), and North America (–26%), whereas benefits in sub-Saharan Africa, East Asia, and the Pacific roughly correspond to the global average (–24%).

Grouping countries by income category instead of by region highlights that young generations in low-income countries will face the strongest increases in lifetime exposure, with a more than fivefold increase for the 2020 birth cohort under current pledges (see fig. S9B). High-income countries face the smallest increases for younger cohorts and the smallest variation across generations. In 2020, 22% of all 60-year-old people lived in high-income countries, whereas only 5% lived in low-income countries. By contrast, only 10% of all newborns lived in high-income countries, whereas 18% lived in low-income countries (see figs. S10 and S11). Thus, children born in the present and future are much more likely to be born in regions facing the highest increase in lifetime extreme event exposure. For example, 64 million children born in Europe and Central Asia between 2015 and 2020 will experience 3.8 to 4.0 times more extreme events under current pledges, but 205 million children of the same age in sub-Saharan Africa face a factor of 5.4 to 5.9 increase in lifetime extreme event exposure, including a factor of 49 to 54 increase in lifetime heat wave exposure (see figs. S10 and S11). This combined rapid growth in cohort size and extreme event exposure (see figs. S10 to S13) highlights a disproportionate climate change burden for young generations in the Global South.

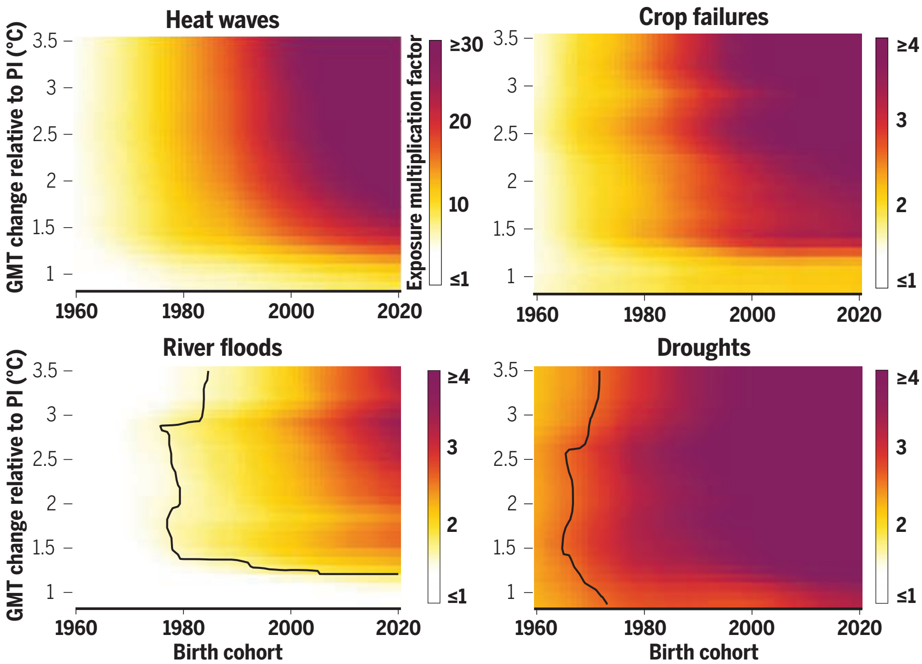
Improvements in life expectancy (see the first figure and fig. S14) represent a confounding factor in the signal of increasing exposure to extreme events over a person's lifetime. However, we found that globally, climate change explains 98% of the exposure increase for the 2020 birth cohort under the current pledges scenario (see fig. S15 and materials and methods). In high-income countries, the enhanced exposure of this cohort is almost entirely attributable to climate change (99%), whereas in low, lower-middle, and upper-middle income countries, climate change contributes 98% of the total exposure change (see figs. S15 and S16).

DISCUSSION

Although we comprehensively account for hazards and exposure in our modeling (*3*, *11*) and attention to within-country population density variability, there are reasons that our approach may underestimate intergenerational differences in exposure (see supplementary text 2). For example, we treated

Lifetime exposure to extreme events on the rise

Exposure multiplication factors across birth cohorts under a range of global warming trajectories (fig. S1) reaching 0.87°C to 3.5°C global mean temperature (GMT) anomalies in 2100 relative to the preindustrial (PI) reference period are shown. Factors are computed relative to the mean exposure of a hypothetical reference person living under PI climate conditions with 1960 cohort life expectancy. The black contours delineate lifetime exposure with 0.01% probability of occurrence under PI climate conditions; absence of the contour indicates that this probability is lower for all cases covered.



multiple extremes within a year as one, neglected compound events (*13*), and ignored changes in event duration and intensity.

In this study, we selected six extreme event categories that have a near-immediate response to warming (*3*), which we can adequately simulate (*11*) and which are known to trigger major impacts (*1*–*9*). We omitted, for methodological reasons, slow-onset events such as coastal flooding (see supplementary text 2). Lifetime exposure to other types of extremes may increase, remain unchanged, or even decrease, such as we found for cold extremes (see supplementary text 3).

Further work could aim at extending this approach to include further demographic dimensions and vulnerability (*14*). Vulnerability to extreme events depends on a range of socioeconomic and demographic factors, such as income or gender, but may also evolve over the course of a lifetime. For example, a young person may experience few health impacts from a heat wave compared with those of older people (*15*), but schooling infrastructure destroyed by a tropical cyclone may have a disproportionate detrimental effect on children's education that could persist throughout their lifetime. And although communities may possibly become less vulnerable to extreme events over time, limits to adaptive capacity remain even under optimistic pathways beyond mid-century (see supplementary text 4) (*14*). Extending our exposure analysis to a comprehensive lifetime risk framework may ultimately inform the further development of climate change adaptation strategies.

Climate change impacts may also engender migration and ultimately even affect life expectancy through increased mortality, two aspects that are not considered in this study. Even though climate change increases mortality (*15*), it is currently not included in life expectancy estimates and population projections such as the ones we used in this work. Likewise, migration triggered by environmental degradation may change both exposure and vulnerability to extreme events. Further analysis should therefore aim at systematically integrating population dynamics and climate risk assessments to better understand the long-term impacts of extreme climate events and to improve socioeconomic scenario development.

Our results highlight the strong benefits of aligning policies with the Paris Agreement for safeguarding the future of current young generations. Lifetime exposure to extreme events drastically increases for younger generations as global warming progresses, especially in low-income countries where strongly rising extremes (*8*) affect a rapidly growing young population. Limiting global warming to 1.5°C instead of following the current pledges scenario nearly halves (–40%) the additional exposure of newborns to extreme heat waves and substantially reduces the burden for wildfires (–11%), crop failures (–27%), droughts (–28%), tropical cyclones (–29%), and river floods (–34%) but still leaves younger generations with unprecedented extreme event exposure. These findings have implications for climate litigation and call for ambitious mitigation to improve intergenerational and international justice. ■

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