https://doi.org/10.1038/s44304-025-00145-9

Population exposure to compound climate extremes: global analysis to identify continent wise age group disparities in a warming world

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The global population faces escalating risks from compound climate extremes, but their future trajectories and differential impacts across age groups and regions remain unclear. This study reveals significant disparities in exposure to compound climate extremes between developed and developing countries, driven by climate and population change, with age-specific insights critical for understanding human vulnerability. Heat-related compound extremes pose the greatest risk, particularly in Africa and Asia. Children and youth are particularly vulnerable in Africa, while in Europe, the elderly are most exposed to both heat and cold extremes. In developing regions, exposure increases most under high population growth scenario, i.e., Shared Socioeconomic Pathway (SSP) 3-7.0, while in developed regions it increases most under the highest warming scenario (SSP5-8.5). Across the world, changing climate is the major contributor to rising exposure for all age groups, more for the younger population, yet in Europe it remains dominant even for the elderly.

The increasing frequency and severity of extreme events, such as heat waves, cold waves, floods, and droughts, pose a significant threat to global ecosystems and human societies[1–3]. Furthermore, the simultaneous or successive occurrence of these events, referred to as compound extremes, exacerbates their impacts, thereby straining socioeconomic resources[4]. Recent decades have witnessed a global increase in compound temperature-precipitation extremes, and this trend is projected to intensify in a warmer future[5]. For instance, regions such as Europe and southern Africa are projected to experience more compound hot-dry extremes, while the eastern USA, eastern and southern Asia, Australia, and central Africa are likely to experience an increase in compound hot-wet extremes[6]. Recent observations further illustrate the severe impacts of these events. Notable instances include the cold-wet event in China in February 2022[7] and the hot-wet extreme in northern India in June 2024[8], both of which caused widespread economic damage.

The risks associated with climate extremes are driven not only by the evolving nature of these events but also by society's vulnerability to them[9]. Demographic shifts and socioeconomic transformations are continuously reshaping the characteristics of the global population, thereby altering future exposure to these extremes. Exposure itself is a critical component of vulnerability, typically understood as a function of three factors: exposure, sensitivity, and adaptive capacity[10]. Thus, the complex interplay between climate change and population dynamics can profoundly influence the exposure and vulnerability of communities to such extremes. Despite this, climate risk assessments have largely overlooked the potential shifts in population size and distribution that could exacerbate vulnerability[11]. The August 2022 heat wave in Europe and the 2015 heat wave in India and Pakistan resulted in thousands of deaths[12], while hundreds perished during the 2006 cold wave in Moscow[13]. These tragedies highlight the increasing risks associated with temperature extremes driven by climate change. Exposure to compound climate extremes could have far-reaching societal consequences. For instance, hot extremes alone can lead to poorer air quality, increased energy consumption, and reduced agricultural yields, and the most concerning of all, negative impacts on human health through heat stress[14]. When combined with drought conditions, these impacts can become even more severe.

Global projections indicate a significant increase in population exposure to compound climate extremes[15]. Notably, the world's two most populous countries, India and China, are expected to experience a substantial increase in exposure to hot-wet extremes[16,17]. Urban areas characterized by high population density are particularly vulnerable. Urbanization is expected to accelerate throughout the 21st century, with the

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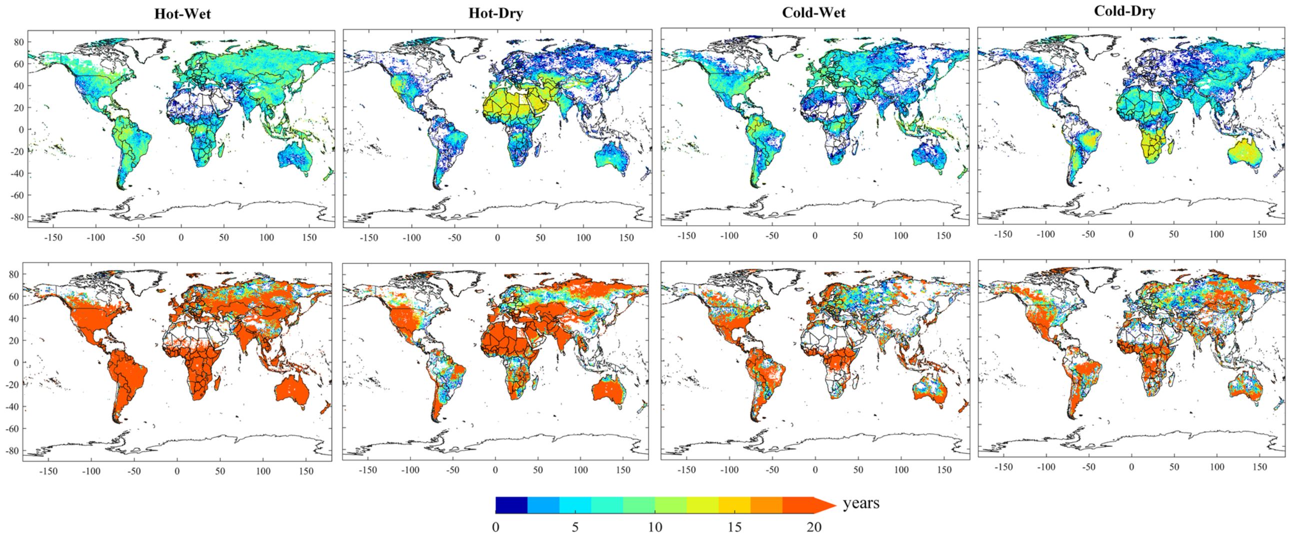

Fig. 1 | Occurrences (number of years) of above-normal compound extreme index (in terms of JEI), i.e., hot-wet, hot-dry, cold-wet, and cold-dry events, during the historical: 1991–2020 and future: 2021–2050 periods, under SSP5-8.5. Figure created using MATLAB, version R2024a.

urban populations projected to grow from 55% of the global total today to 68% by 2050[18]. The majority of this population will be residing in the developing countries, significantly amplifying the challenge of managing the associated impacts.

Vulnerability to a particular compound extreme can vary significantly across different demographic groups, reflecting disparities in exposure and adaptive capacity. Young adults, for example, are particularly vulnerable due to their higher outdoor exposure, which can lead to reduced work productivity and, therefore, significant economic losses in many regions[19]. As climate change accelerates, children born today will face a future characterized by more frequent and intense weather extremes, posing immediate and long-term threats to their physical health and development potential[20]. These challenges are particularly acute in economically less developed regions with rapid population growth, such as Africa and Asia. At the same time, global population aging is emerging as a critical demographic shift[21], with profound implications for the elderly, who are particularly vulnerable to heat stress due to impaired thermoregulatory function[22]. Similarly, children, with their low body mass-to-surface area ratio and limited ability to regulate body temperature, are at elevated risk of dehydration, increasing their vulnerability to heat-related morbidity and mortality[23]. Exposure to compound extremes could further exacerbate these risks.

Despite recent progress in assessing future population exposure, the critical influence of age as a determinant remains largely unexamined. While indices such as the Social Vulnerability Index generally incorporate age-related factors within the sensitivity component of vulnerability[24,25], we extend this perspective by conceptualizing age as an exposure determinant. This approach emphasizes how demographic structure and the absolute size of age groups shape the number of individuals exposed to compound climate hazards, independent of vulnerability characteristics. Given the increasing frequency of compound extremes and changing global demographics, it is crucial to quantify how different age groups are disproportionately exposed to such events. To address these critical knowledge gaps, this study projects the age-specific population exposure to compound temperature-precipitation extremes on a global scale. We focus on four types of compound extremes: hot-wet, hot-dry, cold-wet, and cold-dry extremes, which represent the coincidence of heat waves (or cold waves) either with heavy precipitation or a prolonged dry period. The analysis stratifies the global population into four age groups: children (age < 15 years), young (15 ≤ age < 25 years), adults (25 ≤ age < 65 years), and seniors (age ≥ 65 years) and compares projected exposure for the future period (2021–2050) with the historical baseline (1991–2020). Anticipating how the age-differentiated exposure will evolve over time can guide the development of targeted interventions, particularly in the health, energy, agriculture, and infrastructure sectors, where climate-related risks are expected to intensify.

Results

Projected changes in temperature-precipitation compound extremes

To assess the global population exposure to compound extremes, we first analyse how these extremes are projected to evolve in the future under four different warming scenarios, i.e., SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. Figure 1 and S1–S2 illustrate the global distribution of frequency and average duration of the four compound extremes, providing a comparison between historical observations and future projections. These projections are based on the ensemble average of 19 global climate models (GCMs). The projected increase in hot-wet extremes stands out as the most pronounced among the four compound climate extremes, with increase in global occurrences expected to be nearly 20-fold by 2050 as compared to the reference period. This sharp increase is projected across most regions worldwide, with a few exceptions in northern Russia, south-eastern China, and southern Canada *(*Fig. 1*)*. The hot-dry, another compound extreme, also exhibits significant increases, although to a lesser extent as compared to hot-wet extremes. On the other hand, the cold-dry and cold-wet extremes exhibit relatively smaller increases.

A closer look at the major economies and countries/continents with significant populations and land areas reveals an alarming trend. The world's largest greenhouse gas emitters, i.e., China, the USA, India, the European Union, Russia, and Brazil[26] are projected to experience the steepest rise in compound hot-wet and hot-dry extremes. Australia and Africa will also see a significant increase in such events despite their lower GHG emissions. In contrast, cold-wet extremes are projected to increase, especially in central Africa, the southern USA, South America, coastal Australia, and south-eastern Asia. Additionally, these regions, along with western Russia, are also projected to be affected by cold-dry events.

The average duration of hot spells (WSDI) is projected to increase 2–3 times worldwide under all four SSPs, reflecting a strong and spatially consistent warming pattern that intensifies progressively from SSP1-2.6 to SSP5-8.5 (Fig. S1). Wet extremes (EWD) occurring concurrently with these hot spells are also expected to increase, with the largest rises over humid regions. In contrast, the duration of dry spells (CDD) that coincide with hot spells is projected to exhibit strong regional variability, with substantial increases concentrated across the arid and semi-arid zones. In contrast, cold-spell duration (CSDI) shrinks progressively with higher forcing, yet exhibits pronounced spatial heterogeneity-shortening in much of Africa, Asia, and Australia, yet lengthening in parts of the Americas, northern Europe, central Africa, and East Asia. The wet extremes, concurrent with cold spells, are projected to increase over much of South America, central Africa, and western Asia, while concurrent dry extremes are projected to become more prevalent globally. Overall, the regions that were characterized by specific climatic conditions in the historical period are projected to face increasingly divergent climate extremes, significantly amplifying the challenges of managing their impacts. For example, the predominantly cold Himalayan region is expected to experience a reduction in the duration of cold spells and an increase in prolonged heat waves. In contrast, tropical regions, such as central Africa are likely to witness a significant increase in the frequency of cold spells, putting additional strain on the region's adaptive capability.

Projected change in age-specific population density across the world

Future changes in age-specific population density, compared with the historical period, reveal distinct global patterns with several notable shifts. Considering SSP5-8.5 scenario, the children (age < 15 years) and young (15 ≤ age < 25 years) population are projected to decline significantly (Fig. S6) for most of Asia and Europe. This decline is largely due to the continuing decline in fertility rates. In recent decades, many Asian and European nations are already started experiencing a decline in fertility rates, resulting in a shrinking young population[27–29], and this trend is expected to continue in the future. In developed economies, declining fertility is often attributed to a range of socioeconomic factors, including economic prosperity, delayed marriage, easy access to birth control measures, and the rising cost of childcare. For example, Japan's low fertility rate has been closely linked to declining marriage rates alongside the financial and social burdens associated with raising children[30]. In addition, government interventions such as China's one-child policy also played an important role in accelerating demographic transition.

In contrast, Middle Eastern countries show substantial population growth across all age groups, including the younger populations. This is exceptional as compared to the global trend. This is primarily due to fertility rates that remain above the global average[31]. Similarly, Africa, particularly sub-Saharan Africa, is expected to see substantial growth in younger populations due to persistently higher fertility rates and improvements in healthcare and nutrition that have significantly reduced child mortality[32]. The western United States is also expected to see a modest increase in young populations as compared to eastern United States. However, the current population density is lesser in western United States as compared to eastern United States.

While the future trends in the young population show considerable spatial variation, the senior population (age > 65 years) is projected to increase significantly almost worldwide. This increase can be attributed to the advancements in healthcare, improved living standards, and better disease management, leading to an increased life expectancy. The combined effects of rising life expectancy and the long-term impact of various birth restriction policies like one-child policy in China, are expected to result in a significant increase in the elderly population, coupled with a decline in the younger cohorts[21]. However, there are some striking regional exceptions, such as declining elderly populations in parts of northern Russia, including European Russia and southern South America.

When comparing across pathways (Figs. S3–S6), these regional contrasts become even more apparent. SSP5-8.5 consistently exhibits higher population growth in the USA, Europe, and Australia than the lower-emission pathways, across all age groups. In contrast, Africa, South Asia, and South America show comparatively larger increases under SSP3-7.0. These patterns underscore the divergent demographic trajectories of developed and developing regions, shaped by differences in fertility, age structure, and socioeconomic transitions.

These global demographic shifts, in particular the growth of the elderly population combined with increasing climate-related compound extremes, may amplify the vulnerability of older populations. This will result in significant demands being placed on local governments to develop adequate infrastructure and response systems, especially in less economically developed regions. It is thus essential to gain an understanding of the climate risks in order to identify regions at elevated risk across different age groups, including geographic overlap of demographic change and economic conditions.

Population exposure to compound extremes: recent age-group wise pattern

Analysis with baseline data (1991–2020) shows that hot-wet conditions result in the highest exposure of population among all four types of compound extremes—both in magnitude and spatial extent across the globe. Regions, such as India, Japan, eastern China, western Europe, and parts of Africa, exhibit particularly high exposure across different age groups (Fig. S7). In particular, children and adults face the greatest risks from these extremes, particularly in eastern China, South Asia, and parts of sub-Saharan Africa, often exceeding 1 million person-year. In densely populated regions like South Asia and Africa, where healthcare systems are already strained, the combined impact of heat waves and extreme precipitation events often leads to a severe health crisis.

The young people are also at risk, particularly in South Asia and parts of Africa. The elderly (age 65 and above) are also at similar risk in populous countries, such as India and China, and in developed regions like Japan and Western Europe. In Japan, the elderly population is particularly vulnerable, with exposure levels reaching up to 1 million person-years. This trend is mirrored in eastern China, northern India, and parts of western Europe, where the convergence of aging populations and climate-related factors is exacerbating the risks.

The exposure to the hot-wet extremes is followed by hot-dry and cold-dry extremes causing next levels of population exposure, particularly affecting children and adults in many parts of India, Middle East, and central Africa, and western Europe. Exposure levels in these areas range from 0.6 to over 1 million person-years. Young populations in South Asia and sub-Saharan Africa are particularly vulnerable, while older populations face moderate exposure. The impact of cold-dry extremes is particularly significant in India and eastern China. Interestingly, countries with traditionally exposed to warm climates are now being experienced similar types of compound extremes. For example, India, which is typically characterized by a tropical climate, is increasingly exposed to both heat- and cold wave-related compound events. In contrast, European countries, historically associated with colder climates, are being experienced a rise in heat wave-based compound extremes. Moreover, highly developed countries, such as Japan, with an aging population, are now experiencing significant exposure to both cold-wet and hot-wet extremes. This trend highlights the twin pressures of climate change and demographic change, with profound implications for the elderly.

The shifting patterns of extreme weather events across different climatic and geographic regions underscore the need for a nuanced understanding of how climate change may impact the frequency and intensity of compound extremes worldwide in the future. Equally important are the regional and global population dynamics and the corresponding exposure to these extremes. These insights are critical for guiding the design of targeted adaptation strategies aimed at protecting vulnerable populations from the escalating risks posed by these compound climate extremes.

Population exposure to compound extremes: future age-group wise pattern

Future projections of population exposure under the four SSPs (Fig. S8–S11) indicate a significant increase in future for all the four compound extremes. However, this will vary spatially from region to region across the globe. Hot-wet extremes are expected to continue posing the greatest global risk, followed by hot-dry, cold-dry, and cold-wet extremes, respectively. The higher exposure levels are observed in South Asia and Africa across all age groups and compound extremes. Figure 2 and S12–S14 illustrate the projected

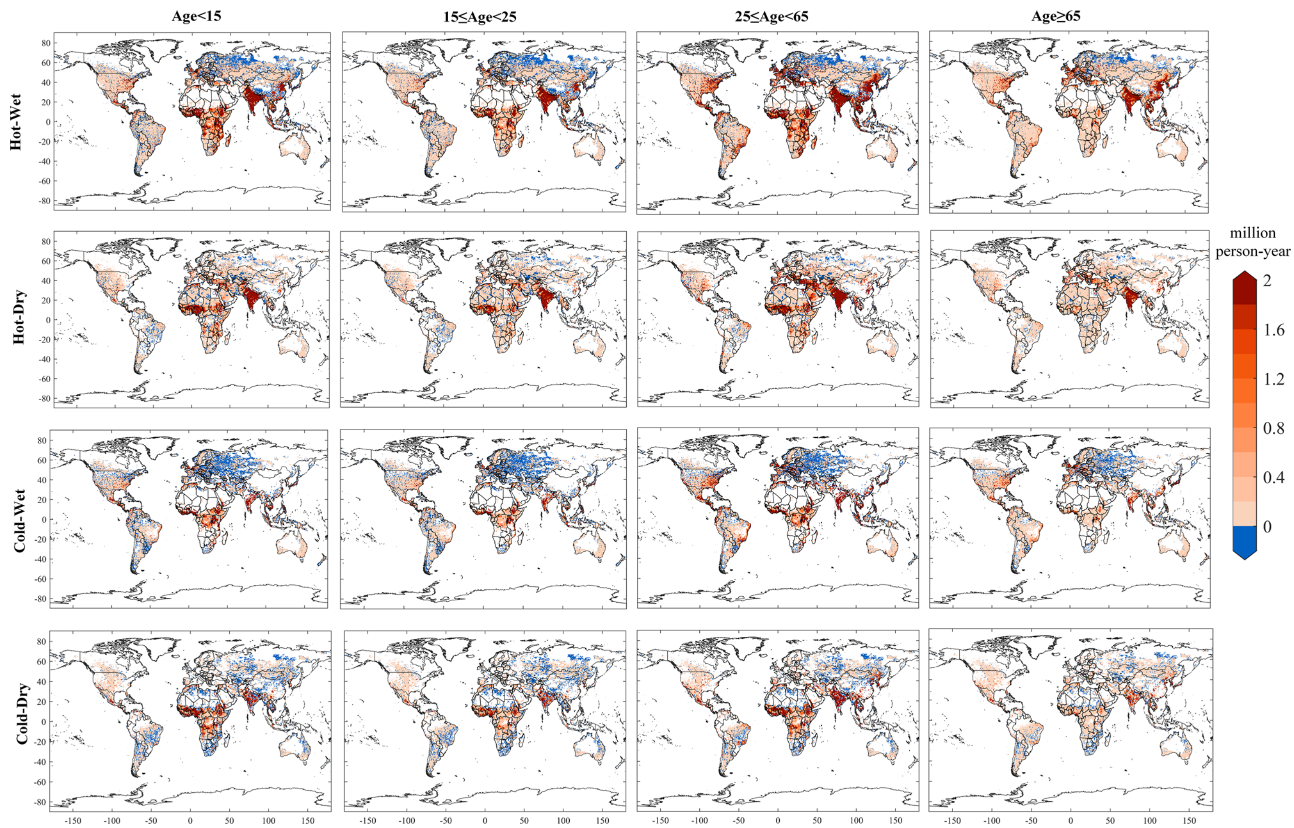

Fig. 2 | Age group wise change in population exposure (in million person-year) from the past (1991–2020) to the future (2021–2050) in the case of SSP5-8.5. Figure created using MATLAB, version R2024a.

future changes in population exposure relative to the historical period. Globally, a large increase in exposure is projected, although some regions may experience a decline. The most pronounced regional contrasts in exposure shifts are observed for hot-wet and cold-wet extremes. Historically vulnerable regions, such as South Asia and sub-Saharan Africa, are projected to experience the largest increases in exposure, reaching as high as 2 million person-years in some areas. Beyond these regions, the eastern USA and Mexico are also projected to experience a significant increase in exposure to hot-wet and cold-wet extremes across all age groups (~0.6–2 million person-years), with the adults and the elderly, particularly at risk.

In contrast, regions where exposure to hot-wet and cold-wet extremes is projected to decrease are mostly concentrated in eastern Europe and northwest Asia, with additional isolated areas across the globe. For cold-dry extremes, the reduction in exposure is projected to be more geographically dispersed in small, isolated clusters, covering all inhabited continents except North America. Conversely, exposure to hot-dry extremes is projected to increase globally, with only a few areas scattered across South America, Asia, and Africa showing potential decreases.

To improve our understanding of how population exposure may vary across different climatic zones (Fig. S16) on a continental scale, aggregated estimates (in billion person-years) at both levels are presented in Figs. 3 and S15 and S17. Globally, the landmass is broadly divided into five major climate zones: arid, cold, temperate, tropical, and polar[33]. The cold and arid zones dominate the global land area, covering approximately 54.8%[34]. However, these regions, however, are characterized by extreme environmental conditions that limit their ability to support large populations. In contrast, the tropical and temperate zones, which together comprise only 32.4% of the land area, support the majority of the world's population. As a result, the highest population densities are concentrated in these regions, especially in Asia. Projections across all SSPs indicate that Asia is expected to experience the highest exposure. This exposure is particularly pronounced for the adult population, with projections ranging from 50 to 60 billion person-years of exposure to hot-wet extremes. Across all climate zones, the same age group is expected to experience the highest exposure, particularly in tropical regions, ranging from 35 to 45 billion person-years. There is a consistent pattern that emerges across all climate zones, with exposure levels decreasing in the order of adults, followed by children, young people, and seniors. However, there is a notable exception: in cold and temperate climates, especially for hot-wet and cold-wet extremes, senior citizens have higher exposure levels than all other groups except adults.

Africa, which is undergoing rapid socioeconomic development, is expected to experience the second-highest exposure to hot-wet extremes after Asia. Due to high birth rates, both children and adults will be significantly affected, with projected population exposure to hot-wet extremes ranging from 12 to 18 billion person-years. In contrast, in highly developed continents like Europe and Australia, the senior population (65 years and older) is projected to experience significant exposure to hot-wet extremes, ranging from 3 to 5 billion person-years across all SSPs. Interestingly, the less developed regions, including Asia, Africa, and South America, are projected to experience the highest exposure to heat-related extremes in SSP3-7.0, while cold-related extremes are most prevalent in SSP2-4.5. In contrast, the developed continents exhibit maximum exposure to all four compound extremes under SSP5-8.5.

Overall, developing continents, such as Africa and Asia, are projected to have significantly higher exposure (up to 60 billion person-years) for the adult age groups under SSP3-7.0 and SSP5-8.5 than developed continents like Europe and North America. In particular, children and young people in Africa are projected to experience compound extremes at much higher rates than in any other region. Conversely, Europe is expected to have the highest exposure of its senior population compared to other continents. However, in relative terms, all continents except Africa are expected to experience a disproportionately higher increase in the exposure of the senior population. North America is expected to see the largest increase, with a projected 20-fold increase in exposure to cold-dry extremes under the SSP2-4.5 scenario.

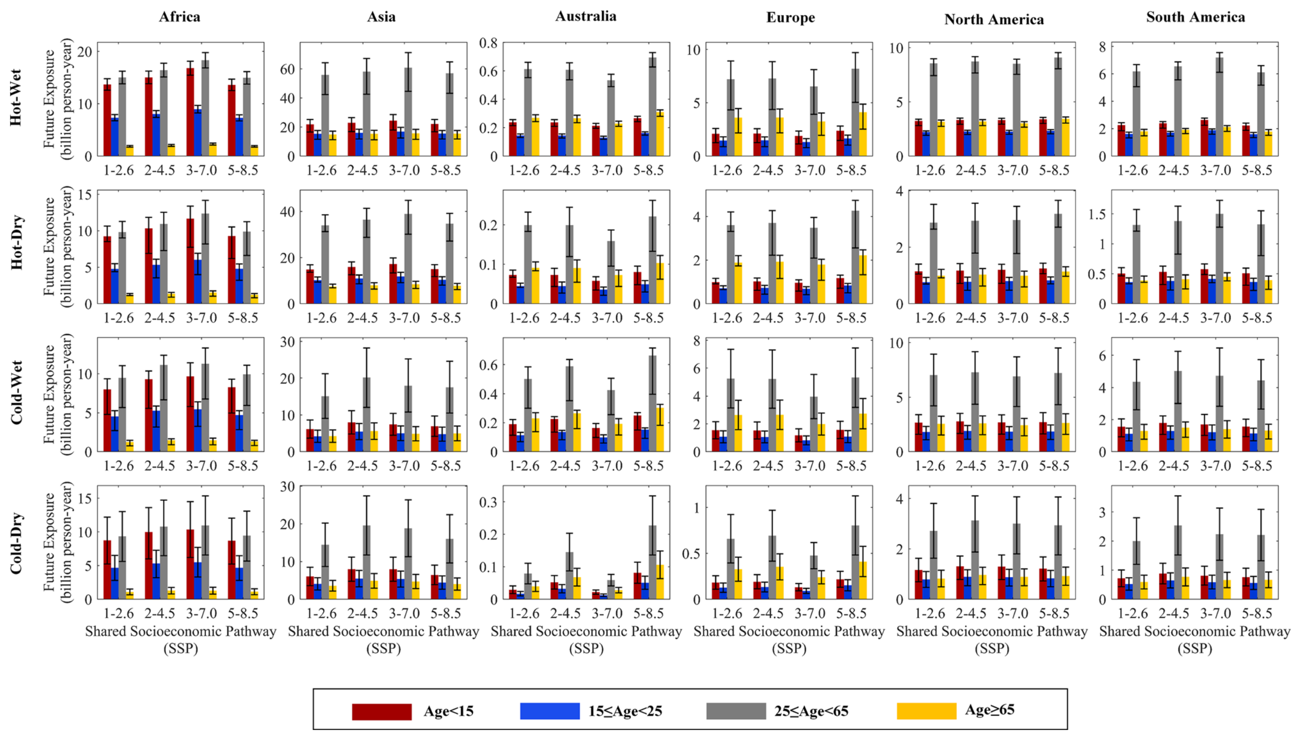

Fig. 3 | Continent-wise future population exposure for the four age groups (denoted through colour of the bars, as shown in the legend) to the four compound extremes expressed in billion person-year during 2021–2050, under four SSPs, i.e., SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. Figure created using MATLAB, version R2024a.

Uncertainty in future exposure varies across regions, age groups, and compound extremes, with the widest ranges in Asia and Africa, given their higher exposure levels. Europe, North and South America exhibit lower absolute exposures but comparable relative spreads, particularly for cold extremes, while Australia shows the narrowest bounds (Fig. 3). Within Africa, dry-related compound extremes carry relatively greater uncertainty, whereas hot-wet extremes generally yield the smallest uncertainty bands across continents, except in Europe. In general, higher uncertainty bounds are revealed for the cold-related extremes. Across scenarios, the lowest uncertainty is found under SSP1-2.6, with the exception of Europe, where it is the lowest under SSP3-7.0. Among the four age groups, the broadest relative uncertainty is obtained in case of the adult age group, reflecting its larger demographic share. These patterns arise from a combination of climate-model diversity in simulating compound events and the masking of sub-regional contrasts when results are aggregated at the continental scale.

Despite these uncertainties, the robust signal is clear: all continents are projected to face substantial population exposure to compound extremes across age groups and emission scenarios, with pronounced disparities between highly developed and less developed regions in terms of overall exposure. Thus, the results are robust for identifying the hotspots of risk, despite variations in precise magnitudes.

While all continents are expected to experience substantial population exposure to compound extremes across all age groups and emission scenarios, there is a pronounced disparity that emerges between highly developed and less developed regions in terms of overall exposure.

Key contributing factor to exposure change: climate vs demography

To develop more targeted and resilient responses to these emerging challenges associated with increasing population exposure to compound extremes, it is critical to have a nuanced understanding of the distinct and combined contributions of climate change and population dynamics. Figures 4 and S18–S32 illustrate the varying contributions of climate change, population change, and their combined effects on shifts in overall exposure across different regions, age groups, SSPs, and types of compound extremes. Notably, climate change plays a dominant role in driving the increasing exposure to compound extremes across all SSPs. This is particularly significant for hot-wet and hot-dry extremes, while it is less influential for cold-related extremes. For hot-wet and hot-dry extremes, climate change makes a consistently positive contribution, significantly increasing the exposure by reaching up to 1.5 to 2 million person-years across all age groups for most of the regions. However, the impact decreases with age, being the most pronounced for children and the least for the elderly.

Population change and the combined effects of climate and population shifts represent a more complex interaction. In younger age groups, these factors make a negative contribution, thereby reducing overall exposure. However, with increasing age, these factors make a positive contribution, especially for senior populations in most regions. The exceptions are southern and central Africa, where population and combined influence contribute positively for all four age groups. In developed regions, such as Europe and North America, the contribution of changes in the younger population is projected to be minimal or even negative. However, the older population is expected to face increased exposure due to population growth. In contrast, developing regions would face a greater level of exposure from both climate change and population growth across all age groups, underscoring the heightened risk in these areas.

Continent-wise future exposure and its three contributing factors across four distinct SSP scenarios (Figs. 5 and S32–S35) reveal that climate change remains the dominant driver of exposure in all scenarios except for the elderly population. For this age group, the combined influence of climate and population changes becomes more pronounced, except in Europe, where climate change remains dominant even for the elderly. Developing regions, such as Asia and Africa, are projected to experience the highest increase in exposure under SSP3-7.0, particularly for hot-related compound extremes. This scenario is characterized by high population growth[35], leading to a substantial increase in both population and combined influences on total exposure. In contrast, in developed regions such as Europe, Australia, and North America, the highest exposure is projected under SSP5-8.5, which assumes lower population growth, while the lowest exposure is projected under SSP3-7.0. As a result, developed regions like Europe,

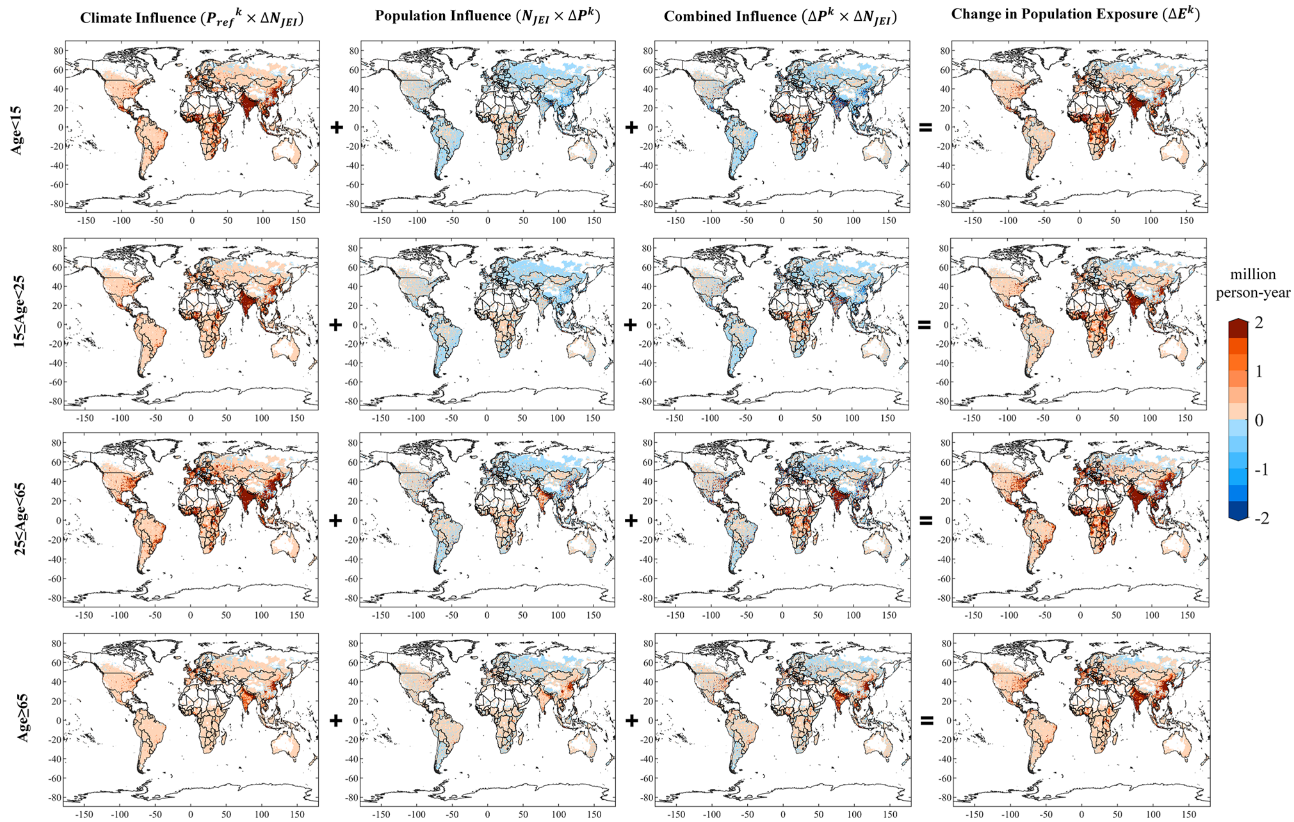

Fig. 4 | Change in population exposure to compound hot-wet extremes, along with corresponding contributions from climate influence, population influence, and combined influence, expressed in million person-years, under SSP5-8.5 across the four age groups. Figure created using MATLAB, version R2024a.

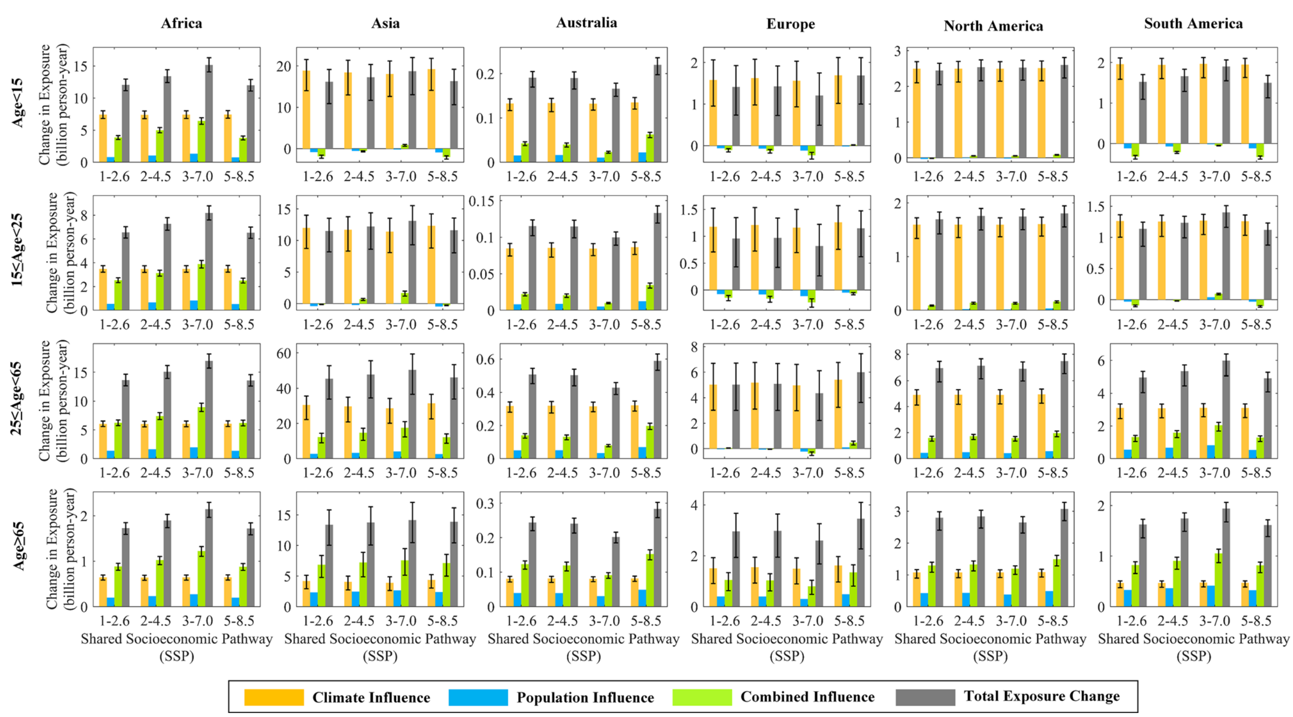

Fig. 5 | Continent-wise contributions from climate influence, population influence and combined influence, along with the total change in future population exposure (denoted through colour of the bars, as shown in the legend), for the four age groups, considering hot-wet compound extremes expressed in billion person-year during 2021–2050, under four SSPs, i.e., SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. Figure created using MATLAB, version R2024a.

Australia, and North America will experience maximum exposure under SSP5-8.5 and the least under SSP3-7.0. For cold-related compound extremes, maximum exposure is generally projected under SSP2-4.5, except in Africa, where the highest

Synthesizing the influences of both climate and population dynamics reveals the overwhelming impact of climate change as the primary driver of exposure, with demographic shifts further amplifying its impact. This is particularly pronounced in regions where significant population growth is occurring alongside significant climatic change, increasing the risks and complexity of managing and mitigating exposure. This highlights the variability in how climate and population factors affect different regions and age groups, necessitating tailored responses to mitigate the risks of compound extremes in vulnerable populations.

Discussion

This study presents a comprehensive assessment of the historical (1991–2020) and future (2021–2050) projected exposure of different age groups to compound temperature and precipitation extremes. We also assess the influence of three key drivers: climate change, population growth or decline, and the interaction between the two on the exposure levels, revealing significant variation across age groups, regions, type of compound extremes, and SSPs.

Compound hot-wet and hot-dry extremes are projected to intensify sharply worldwide, with particularly pronounced increases in both humid and arid regions. In contrast, cold-related extremes exhibit strong spatial variability, declining in many tropical and subtropical regions but intensifying in parts of the Americas, northern Europe, central Africa, and East Asia. These patterns are consistent with earlier studies[36]. These contrasting trends indicate that historically characteristic climate regimes will increasingly diverge, with regions facing both amplified heat risks and persistent or even heightened cold-related hazards.

Heat wave-associated compound extremes lead to the highest global population exposure and pose the greatest global risk in both historical and future contexts. Asia and Africa are projected to experience the greatest future exposure to these compound extremes, particularly among children and adults, underscoring the heightened vulnerability of developing regions. Of particular concern is sub-Saharan Africa, where younger populations are projected to be disproportionately exposed to compound extremes compared to all other regions. These results reinforce earlier findings that developing regions will face disproportionate increases in exposure to hot-dry and hot-wet extremes[37,38]. Conversely, in developed regions such as Europe, Australia, and North America, the elderly populations are expected to be most exposed to hot-wet and hot-dry extremes. Europe, in particular, is projected to have the highest exposure levels for its senior citizens, highlighting the increased risks for an aging population. The United States is expected to experience a significant increase in hot-wet and cold-wet extremes, particularly in the eastern regions. Of all age groups, adults will experience the highest overall exposure globally, driven by their large population size. In Asia, for example, adults will face up to 60 billion person-years of aggregated exposure under the SSP3-7.0 and SSP5-8.5 scenarios.

Our results show that climate change is the main driver of increased exposure to all four compound extremes, with demographic shifts exacerbating this impact across all SSPs. Notably, the senior population represents an exception, where the combined influence of both climate and demographic shifts results in a more pronounced impact. This underscores the rapid population aging in many regions, compounding their vulnerability to both environmental and societal pressures. Given their heightened vulnerability, linked to cognitive or physical limitations, inadequate housing or income, and limited family support—elderly individuals should be a central focus of climate hazard response strategies. Challenges are particularly acute in Asia and Africa, where exposures are the highest and adaptive capacity lowest, creating mounting pressures on health and social services and underscoring the need for novel policy interventions[12]. In Europe, however, demographic growth is relatively stable or even declining, and population aging has already progressed substantially. Consequently, demographic change contributes less to exposure increases, and climate change remains the dominant factor, even for seniors. This aligns with recent studies showing that in Europe, climate-related intensification accounts for the majority of future heat-related health risks, while demographic change adds only a marginal share[39,40].

There is a marked disparity between developed and developing regions with regard to overall exposure and the relative influence of contributing factors. In developed regions, population growth is projected to have minimal or even negative effects on exposure levels for the younger age groups. Conversely, the senior population is expected to face increased exposure due to both climate change and population growth. In contrast, developing regions would face a greater level of exposure due to both climate change and population growth across all age groups. Furthermore, the highest increase in exposure to heat-related compound extremes is projected in developing regions under the high population growth scenario, SSP3-7.0. In developed regions, the highest exposure is expected under SSP5-8.5, which assumes lower population growth, and the lowest exposure is observed under SSP3-7.0. Cold-related extremes generally show the highest exposure under SSP2-4.5, except in Africa, where SSP3-7.0 dominates. While these results are robust in identifying hotspots of exposure, uncertainties remain due to climate-model diversity. Notably, the relatively low uncertainty ranges associated with hot-wet extremes suggest a strong level of agreement across models. However, for cold-related compound extremes, the uncertainty ranges are relatively higher, suggesting a weaker agreement between models. These uncertainties emphasize that the findings are best interpreted as indicative of broad trends rather than precise numerical projections, yet they still provide a reliable foundation for guiding adaptation planning.

In summary, our findings have considerable implications for policymakers and stakeholders seeking to reduce the adverse impacts of compound temperature-precipitation extremes on vulnerable populations. To effectively manage and mitigate increasing exposure, interventions must be region-specific and tailored to different age groups, recognizing the distinct vulnerabilities within each demographic group. By incorporating demographic trends into climate adaptation planning, policymakers can improve the precision and impact of their policies and more effectively address the unique risks faced by different population groups.

Methods

Climate and population data

The hourly climate (precipitation and temperature) dataset for the reference period is obtained from the European Center for Medium-Range Weather Forecasts Reanalysis 5 (ERA5)[41], and daily precipitation, maximum temperature, and minimum temperature are calculated. The bias-corrected future climate data for the four future scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) are obtained from the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6) archive for 19 GCMs (Table S1), based on data availability. The four SSPs combine socioeconomic trajectories with different climate forcing levels[42]: SSP1-2.6 follows a sustainability pathway with low emissions and slow population growth; SSP2-4.5 represents a middle-of-the-road trajectory, with moderate population growth; SSP3-7.0 projects the highest growth, especially in developing regions, driven by inequality and weak investments in health and education; SSP5-8.5 envisions rapid fossil-fueled economic growth, with population peaking mid-century before declining due to low fertility. The total population for the reference period and the population shares of different age groups for both the reference and future periods are obtained from hybrid gridded demographic data repository[43]. The future population data for different SSPs are obtained from the NASA Socioeconomic Data and Applications Center (SEDAC)[44]. The future age-group population fraction dataset is considered to be consistent across the four SSPs, and all the datasets are regridded to a common horizontal resolution of $0.5^{\circ} \times 0.5^{\circ}$.

Temperature and precipitation extreme indices

Four univariate indices, i.e., Warm Spell Duration Index (WSDI), Cold Spell Duration Index (CSDI), Consecutive Dry Days (CDD), and Extreme Wet Days (EWD), are considered, which express extreme precipitation and temperature conditions. Among these four indices, WSDI, CDD, and CSDI were developed by the Climate Variability and Predictability (CLIVAR) project of the World Climate Research Programme in collaboration with the Expert Team on Climate Change Detection and Indices (ETCCDI) (https://www.wcrp-climate.org/data-etccdi, accessed on July 2024), while EWD was proposed in Dash and Maity[45] and Dash et al.[17]. WSDI is defined as the prolonged periods (6 or more consecutive days) of excessive heat when daily maximum temperatures exceed the 95th percentile threshold. CSDI identifies the periods of intense cold, when the daily minimum temperature falls below the 5th percentile, for 6 or more consecutive days. CDD reflects prolonged periods of very little (less than 1 mm) or no precipitation. EWD identifies the number of days when daily precipitation exceeds the 95th percentile threshold, denoting the heavy precipitation event. Thus, summarizing the definitions, WSDI, CSDI, CDD, and EWD identify hot, cold, dry, and wet extremes on an annual basis.

Conceptualization of compound extremes

The four univariate indices, i.e., WSDI, CSDI, CDD, and EWD, are combined using copula functions to obtain the Joint Extreme Indices (JEIs) of hot-dry (WSDI-CDD), hot-wet (WSDI-EWD), cold-dry (CSDI-CDD), and cold-wet (CSDI-EWD) extremes. Conceptually, a hot-wet extreme is identified when a heavy precipitation event (identified by EWD) occurs within $\pm n$ days ($n = 10$ days in this study), centered around a specific hot spell of m days (identified through WSDI). Conversely, a hot-dry extreme is identified when dry conditions (precipitation < 1 mm) persist for the entire preceding and subsequent n days centered around the extreme hot spell. Similarly, cold-wet and cold-dry events are also identified in a similar way. For each year, the number of extreme temperature days and the number of extreme precipitation days form two individual time series, i.e., Temperature Extreme Index (TEI) and Precipitation Extreme Index (PEI), respectively.

Characterization of compound extremes utilizing copulas

For the next step, the Joint Extreme Index (JEI) representing compound extremes is developed by combining the standardized TEI and PEI. Consider the example of hot-wet compound extremes. A joint distribution between TEI (WSDI) and PEI (EWD) is developed using copulas. Similarly, JEI values for other compound extremes are developed using their constituent PEI and TEI. Archimedean copulas, namely Frank, Clayton, and Gumbel-Hougaard, are used, and the best-fit copula is identified based on the goodness-of-fit tests. The best-fit copula may vary from location to location, as per the dependence structure between the corresponding extreme indices. Once the joint distribution is determined, the non-exceedance probability is obtained, and it is standardized to obtain the JEI. Further details of this method can be found in Dash et al.[17]. It is worthwhile to mention here that the best-fit copula and its parameters were first identified from historically observed PEI and TEI, and then used as a fixed baseline for projecting future joint distribution by incorporating the PEI and TEI projected under the four SSPs. This allows a consistent comparison of shifts in the frequency and intensity of compound extremes under changing climatic conditions. Holding the dependence structure constant thus provides a consistent and interpretable reference frame for comparative assessment across different time periods. While non-stationary copulas with time-varying parameters may better capture evolving dependence structures, exploring such approaches is kept as an important avenue for future research scope.

Assessment of population exposure

The final step is to assess the population exposure to compound extremes for different age groups. The total population is divided into four different age groups, i.e., children (age < 15 years), young (15 ≤ age < 25 years), adults (25 ≤ age < 65 years), and seniors (age ≥ 65 years). The age categories used in this study follow internationally recognized demographic standards widely adopted by the United Nations, UNESCO, and the Population Reference Bureau (PRB)[46–49], reflecting key life stages relevant to dependency, workforce participation, and vulnerability. Specifically, individuals under 15 are classified as children due to their dependence and non-participation in the labour force; those aged 15–24 represent the transition from education to early employment; the 25–64 group corresponds to the prime working-age population; and 65 years and above age group aligns with the conventional retirement age and increased age-related risk.

Considering a given grid, the JEI value corresponding to each year is obtained. Next, population exposure by age group to the compound extremes is calculated by multiplying the number of years with above-normal JEI values (i.e., JEI > 0) by the corresponding total population by age group, averaged over a given time period. It is expressed in person-years.

$$E^k = N_{JEI} \times P^k \tag{1}$$

where, $k = age < 15\,,\ 15 \le age < 25,\ 25 \le age < 65 and\ age \ge 65$

E^k is the age group-wise (i.e., k) population exposure, and P^k is the mean age group-wise population count. N_{JEI} is the number of years with above-normal compound extreme occurrences.

The study then focuses on quantifying the three drivers of change in population exposure: climate change, population change, and the combined effect of the two. The expression for the change in population exposure (ΔE^k) in the future period, relative to the reference period, is given by –

$$\Delta E^k = P_{ref}{}^k \times \Delta N + N_{JEI} \times \Delta P^k + \Delta P^k \times \Delta N \tag{2}$$

$P_{ref}{}^k$ is the average age group specific population for the reference period, and ΔP^k reflects the corresponding change in the future period relative to the reference period for four different age groups (k). Similarly, N_{JEI} and ΔN represent the number of years with above-normal compound extreme occurrences in the reference period and corresponding changes in the future, respectively. $P_{ref}{}^k \times \Delta N$ is the contribution due to climate change, $N_{JEI} \times \Delta P^k$ is the contribution due to population change of different age groups and $\Delta P^k \times \Delta N$ is the contribution due to change in both, i.e., the combined effect.

Data availability

All data used in this study are available online. The ERA5 reanalysis data are available from https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview. The bias-corrected NEX-GDDP-CMIP6 datasets are available from https://nex-gddp-cmip6.s3.us-west-2.amazonaws.com/index.html#NEX-GDDP-CMIP6/. The gridded global population datasets are available from https://earthdata.nasa.gov/data/catalog/sedac-ciesin-sedac-gpwv4-popcount-r11-4.11. The age-wise population fraction data is available from https://zenodo.org/records/3768003. Köppen-Geiger climate classification of the World is generated using the open-access dataset, available from https://www.gloh2o.org/koppen/.

Received: 25 April 2025; Accepted: 7 September 2025;
Published online: 13 September 2025

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Acknowledgements
We acknowledge the ECMWF, NASA Center for Climate Simulations (NCCS-THREDDS), and NASA Socioeconomic Data and Applications Center (SEDAC) for the availability of the historical and future climate and population datasets. We also acknowledge the National Supercomputing Mission (NSM) for providing computing resources of 'PARAM Shakti' at IIT Kharagpur, which is implemented by C-DAC and supported by the Ministry of Electronics and Information Technology (MeitY) and Department of Science and Technology (DST), Government of India. The work is partially supported by the sponsored projects supported by the Ministry of Earth Sciences (MoES), Government of India, through a sponsored project. Author Rajib Maity acknowledges support from the Alexander von Humboldt-Stiftung/Foundation as a Humboldt Fellow.

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Conceptualization: R.M. and H.K.; Methodology: S.D., S.S.M., R.M., and H.K.; Formal analysis: S.D. and S.S.M.; Investigation: S.D., S.S.M., R.M., and H.K.; Writing—original draft preparation: S.S.M. and S.D.; Writing—review and editing: R.M. and H.K.; Funding acquisition: R.M. and H.K.; Resources: R.M. and H.K.; Supervision: R.M. and H.K.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s44304-025-00145-9.

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