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Article

The Impact of Climate Change on Environmental Sustainability and Human Mortality

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Abstract: Climate dictates the critical aspects of human environmental conditions. The frequency and intensity of extreme weather conditions due to human-induced climate change have alarmingly increased. Consequently, climate change directly affects environmental sustainability and human mortality in the short term and creates prolonged and complicated long-term indirect grave risks. This paper examines three-level environmental impact risks associated with climate change on human mortality. It proposes a conceptual framework for developing an empirical event-based human mortality database related to climate change and communication strategies to enhance global environmental adaptation, resilience, and sustainability.

Keywords: climate change; remote sensing; science communication; human mortality; global sustainability

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1. Introduction

Climate change may not always kill people directly at a particular location, but it creates extreme environmental conditions and threats, which in turn cause acute and chronic morbidity premature and preventable human mortality in many areas globally. Climate change dictates many aspects of the human environment. It has imposed major threats worldwide, such as monstrous tropical storms, extreme heat waves and cold winter storms, droughts, wildfires, floods, and landslides. Much progress has been made in recognizing the importance of climate change research. Climate change is believed to be the most significant global health threat of the 21st century; human mortality in US cities is reportedly highest on extremely hot, humid summer days, but winter mortality rates are significantly higher than summer rates [1,2]. Still, not enough attention has focused on monitoring, measuring, and communicating climate change in terms of human mortality. There have been no large-scale, systematic efforts to quantify the heat-related human health impacts associated with climate change [3]. There is no established database on human mortality specifically related to climate change at any level, such as by town or city, by region, by nation, and for the entire world.

Human-induced climate change has complicated and augmented the effects of environmental changes. Consequently, climate change triggers many environmental hazards and extreme conditions that threaten human health and survival, potentially reaching the tipping point of collapse. Climate change's accumulative and compound effects on human mortality must be effectively, urgently monitored and communicated. The impact risks and damages of climate change are not evenly distributed, and the poorest countries will likely be affected strongest by rising climate-related disaster risks in a warmer world [4,5].

Climate change's long-term and accumulated effects on human mortality likely go beyond the magnitude of grave natural disasters such as earthquakes and volcanic eruptions.

Humans are both the agents of climate change and victims of adverse consequences due to the change. The spatial and temporal variations of human mortality communicate a broad dynamic imbalance of environmental sustainability related to climatic change.

2. Primary Environmental Impacts of Climate Change

Climate change research has gained more momentum over the last few decades. A plethora of environmental risks associated with climate change have been gradually brought forth to focus. The impacts of climate change can be at multiple levels with different time frames. To better understand them, we further categorize and examine them as primary, secondary, and tertiary impact risks.

The primary impacts of climate change directly led to abnormal environmental conditions such as sea level rises, intensified tropical storms, floods, extreme heat waves and wildfires, and cold winter storms. As global warming continues, the ocean surface temperature will continue to increase, more glacier ice will melt, and sea level will rise. The estimated 100-year extreme sea-level event will become an annual (or more frequent) event by 2100, making the tropics more vulnerable [6]. The frequency and intensity of tropical storms will likely amplify and intensify.

Figure 1 shows the major potential primary impacts of climate change, which can all impact human mortality. Dynamic imbalance among Earth-Sun energy flow produces extreme weather patterns, resulting in abnormal sea level rise and adverse temperature and precipitation distribution patterns. The world will face substantial increases in the frequency of the most intense tropical cyclones, with intensity increases of 2–11% by 2100 and increases of 20% in the precipitation rate within 100 km of the storm center [7]. The storm surge inundation volume and extent are projected to increase over the century in the U.S., more notably along the Gulf Coast (Texas, Louisiana, Mississippi, and the West Coast of Florida), the Carolinas, and New Jersey [8]. Accelerated polar ice loss and sea level change are directly related to climate change, and it is reported that three-quarters of Arctic ice by volume has been lost in only 40 years, which provides more fuel for tropical storms and faster sea-level rise [9].

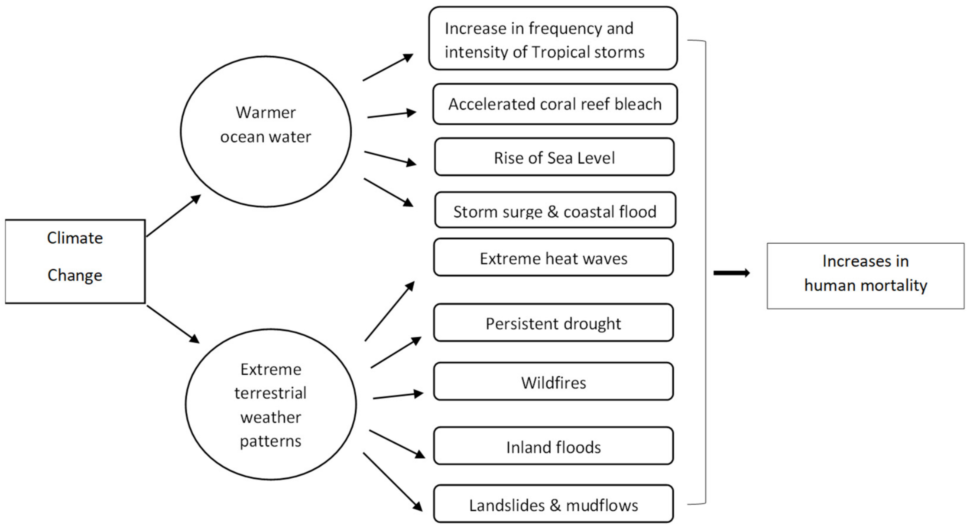

Figure 1. The potential impact of climate change on the environment and human mortality.

Projection modeling studies indicate that future tropical cyclones will continue to increase in their maximum intensities and related rainfall [10]. More people and properties along the coastline will be threatened and affected. More coral reefs and lowlands will take the forefront brunt impacts from multiple aspects, such as tropical storms, increased seawater temperature, the rise of sea level, and increased discharge of sediments and chemicals from the land. The bleached or damaged coral reef structures will directly affect the habitats of marine organisms and coastal fishery. Coral reefs are likely to degrade rapidly over time, presenting fundamental challenges for an estimated 500 million people who derive food, income, coastal protection, and a habitat for some of the highest regions of biodiversity in the ocean [11,12].

The impact on land is often manifested in a variety of different ways. Climate change creates abnormal weather patterns. Extreme temperatures and abnormal precipitation have caused persistent heat waves, extreme cold storms, droughts, widespread wildfires, major inland floods, landslides and mud flows, urban heat islands, and air pollution.

The increase of both mean and extreme temperatures presents threats to biological adaptation. Heat waves become more frequent, intense, and long-lasting in many regions worldwide, and extreme temperature variations, especially humid heat, affect human health and mortality [13,14]. In a severe heat wave of the summer of 2003, data analysis suggests that anthropogenic climate change caused up to seventy thousand excess deaths across Europe, increased the risk of heat-related mortality in central Paris by ~70% and by ~20% in London where they experienced the lower end of the extreme heat [2]. It is estimated that the severe heat waves will triple at the end of the 21st century [15]. The most severe heat wave events will reach the limits of survivability due to the fatal combination of rising temperatures and humidity levels [16].

Wildfires of unprecedented scale and duration have occurred worldwide recently. The ongoing record-breaking 2023 wildfires in Canada serve as a significant wake-up call, according to the government of Canada. Wildfires in Australia from 2019 to 2020, Brazil in 2019 and 2020, the western United States in 2018 and 2020, British Columbia, Canada in 2017 and 2018, and Southern Europe in 2017 [17,18]. The burning areas from climate warming are projected to rapidly increase over the Mediterranean region: the higher the warming level, the larger the burning area increases from ~40% to ~100% across different warming scenarios [19]. In recent years, immense and severe fires in the Pacific Northwest have been associated with warm and dry conditions, and wildfires will likely occur with increasing frequency driven by the warming climate [20]. The onslaughts from both ocean and land have posed significant threats to human health and survival.

3. Secondary Environmental Impacts of Climate Change

The primary environmental impacts of climate change, such as sea level rise and abnormal severe weather patterns, subsequently and consequently lead to compound lingering environmental risks. Those primary environmental risks often trigger secondary environmental risks, such as agricultural productivity, food supply, terrestrial and marine ecosystem disruption, air pollution, infrastructure and resources damage, and economic damage and loss. Indirect losses, such as loss of jobs or business interruption, as well as other consequential economic losses, may last months or years after the disaster [4].

The primary threats to the physical environment expand into ecological, economic, and socio-economic problems. The environmental risks cause major disturbances and damages to both marine and land ecosystem functions, which trigger the decline of seafood supply and crop yield; infrastructure damage; the availability and reliability of energy, clean air, water, and other resources; the access to transportation and health care, the shift of job markets; and the overall decline of economic activities and productivities.

The impact of warming on annual economic growth, for decades, has accumulated substantial declines in economic output in hotter, poorer countries [4,21]. Contrary to coastal floods from tropical storms, accessibility to reliable water resources in many other regions is an even more alarming issue associated with climate change. Climate change alters precipitation patterns and may substantially aggravate the water scarcity problem [22,23].

Energy is essential to socioeconomic functions, overall development, and the quality of living. Adequate access to energy is encumbered by infrastructure, affordability, and service disruptions due to disasters and extreme weather events, often linked to climate change [24]. Yet, energy consumption and climate change have a complicated relationship. Fossil fuel consumption contributes to climate change and affects energy security. Climate change and energy security are two interlinked but separate problems for many countries, differing in how to deal with the clash of energy security, access, and affordability with sustainability [25]. It is estimated that nine out of ten major outages in the US have been caused by hurricanes, and long-term outage risk is a function of climate change-triggered hurricane frequency and intensity [26].

Global and domestic food production and supply systems are directly and indirectly impacted by a changing climate [27,28], and yet limited attention has been paid to the nexus of climate change, food security, and human health, resulting in knowledge gaps regarding food system components that are most vulnerable to climate change [29]. Climate change and agriculture productivity have inextricable links, and abrupt changes in climatic conditions have threatened food security at a global scale, substantially contributing to reduced production, food affordability, and food security for the needs of the growing population [30]. Recent data indicate approximately 800 million people are undernourished, out of which 780 million reside in low-to-middle-income countries, and people start to ponder whether malnutrition is a cause or consequence of poverty [31,32]. As the world population grows, the food supply and nourishment problem can only worsen. Undernutrition is a significant contributor to the global burden of diseases, and global health impact models suggest that climate change will cause reductions in food quantity and quality [33].

The impacts of climate change are larger, more complex, and more uncertain than any other environmental problem [34]. Climate change affects workers worldwide through the loss of jobs, the changing of jobs, and the creation of new jobs [35]. If the total economic impact is negative, the overall job impact will be negative as well. It is estimated that the global economic output will reduce by 7–14% by the end of the century, with even greater damages in tropical and poor regions if there is an increase in global mean surface temperature by about 3.5 °C [36]. Job loss and economic decline can drastically increase stress factors and cause human morbidity and mortality.

4. Tertiary Environmental Impacts of Climate Change

The primary and secondary impact hazards can exasperate and cascade into lingering short and long-term tertiary risks, such as geopolitical conflicts, social interruptions, acute and chronic physical illnesses, and mental health risks. The primary and secondary environmental risks often lead to delayed and amplified morbidity and mortality issues due to chronic illnesses and persistent socioeconomic stressors. The broader environmental stress factors can exert widespread socioeconomic impacts, such as community conflicts and an individual's ability and resilience to overcome the challenges.

To compound the problems, not all nations, regions and individuals face the same threats and have the same resources and capacity to overcome challenges and mitigate problems associated with climate change. Poor countries not only have not shared the full benefits of fossil fuel energy consumption, but many have already been made poorer (in relative terms) and impacted more by climate change due to the energy consumption of wealthy countries [22].

Accurate monitoring and assessment of climate change impacts on the global economy and national incomes is complex, but the relative damages from not complying with the Paris Climate Accord will be especially severe to the vulnerable Sub-Sahara Africa, India, and Southeast Asia regions, regardless of the range of temperature change [37]. Greater damages will likely be on the national economic output in the future for the tropical and poor regions [37]. The social cost of carbon (SCC) will increase for almost all countries. However, it tends to be higher in hotter, poorer regions, such as South and Southeast Asia and sub-Saharan Africa [38].

Within developed countries, some people are more vulnerable to the impact of climate change. The poor, the elderly, the disabled, children, prisoners, and substance abusers in the U.S. are found to have experienced heightened levels of mental, emotional, and bodily stress due to natural disaster exposure; the mental and physical health of marginalized populations during and after a natural disaster were elevated and/or exacerbated by circumstances pertaining to the weather event and the lack of disaster-response actions [39].

Hurricanes and other tropical cyclones have far-reaching, devasting effects on human health and mortality, such as deaths, injuries, onset of new illnesses, and lasting mental health issues. A recent study found that hurricanes and tropical cyclones are associated with, on average, increases in the overall number of hospitalizations following tropical cyclone wind exposure, especially related to the largest increases in respiratory diseases and injuries based on the data over 16 years [40]. Columbia University's Mailman School of Public Health [40] research reports that hurricanes and tropical cyclones were associated with up to 33.4 percent higher death rates from several major causes in subsequent months in the U.S. during recent decades. Hurricanes directly cause injuries and exacerbate multiple diseases, with most adverse health impacts peaking within six months following hurricanes, while chronic diseases, including cardiovascular disease and mental disorders, may not surface until many months after the hurricanes and can continue to occur years following the initial impact [41].

Wildfires intensified by climate change are estimated to contribute an average of 71.3% of total $PM_{2.5}$ and impose millions of people to wildfire smoke exposure [42]. Climate change increases the frequency and intensity of heatwaves and wildfires and causes a synergistic effect of air pollution and high temperatures, air pollution change, and allergen patterns [43].

The deterioration of environmental conditions may facilitate the transmission of infectious diseases, cardiovascular and respiratory illnesses, and malnutrition and indirectly cause mental health problems due to stress, loss of homes, economic instability, and forced migration [44]. The prolonged and accumulated impacts will likely lead to geopolitical conflicts and cause long-term chronic physical and mental health problems. A recent study suggests that exposure to extreme or prolonged weather-related events can also be delayed, encompassing disorders such as posttraumatic stress, or even transmitted to later generations [45].

The impact of climate change has a long wavelength disturbance cycle. A study indicates that long-term climate change has been a driver of worldwide and synchronistic war–peace, population, and price cycles in recent centuries [46]. Military conflicts cause acute human health and mortality problems and contribute to the vicious cycle of climate change as they often destroy healthy ecosystems and deplete more natural resources.

Tertiary impacts will be amplified, and far-reaching as ecological and economic problems create systemic social dysfunctions. Climate collapse, which might not be an abrupt event but rather an extended process, starting small and playing out over the course of a century or more, could potentially lead to global civilization collapse and significant world population decline [47].

5. A Global Event-Based Human Mortality Database Related to Climate Change

Climate change has caused a significant impact on the earth's ecosystem and, consequently, human health issues and mortality. According to the WHO website on climate change and health, "between 2030 and 2050, climate change is expected to cause approximately 250,000 additional deaths per year, from malnutrition, malaria, diarrhea and heat stress." A recent study of global climate indicates up to 5 million deaths a year linked to abnormal temperatures [48]. The U.S. EPA indicates more than 11,000 Americans have died from heat-related causes from 1979 to 2018. There is a growing need for an evidence-based ground-level empirical database of climate change on human mortality.

Yet, there are no concerted global efforts in tracking human mortality from individual extreme weather events related to climate change, such as tracking mortality rate and rate change from major climate-related hazards at a specific given geographic location over time. The current mortality estimations and projections largely focus on analyzing the relationships between different climatic factors and existing aggregated daily mortality data. Recent studies simulated subnational and global extreme weather conditions and daily mortality data to predict the future mortality trend through different climate model scenarios [49–52].

These large-scale studies on climate change and mortality are generally done in a coarse spatial resolution, such as national and global scales. The climate data are long-term average weather conditions. As such, at any given location, extreme weather conditions do deviate from climate normal. The mortality data are aggregated records. The mathematical and statistical relationships between climate data and indiscriminating daily mortality data inevitably contain errors of omission and commission. The simulated mortality projection rates can be modulated by using climate data (error of omission) or amplified (error of commission) using non-discriminate mortality data, including the mortality data from other causes, such as earthquake and volcanic disasters and human-induced spill/pollution and violent conflicts.

The relationships between climate and extreme weather conditions are complex; many attribution studies have contrasting views and conclusions. In the attribution studies in the Bulletin of the American Meteorological Society report from 2012 to 2017, roughly 65% have found that climate change increased the severity or likelihood of a severe weather event, and the rest did not find a significant contribution from climate change [53]. In many parts of the world, severe droughts are not attributable to climate change [54]. For any extreme weather event, the contribution of anthropogenic climate change to the event is often questioned [55]. Despite the limitations and uncertainties, GCMs are essential tools for studying the dynamics of the most extreme events and simulating the general tendencies of regional and global trends and patterns [50,56].

The impacts of climate change on human mortality include primary, secondary, and tertiary effects of severe weather and long-term climate drivers. To get a more accurate fine resolution of the geospatial impacts of climate change on human mortality, an event-based mortality database is critical. Climate models are important for large regional and global analysis to simulate the secondary and tertiary impacts, while an event-based mortality database will allow the studies of primary impacts of extreme weather conditions and help track the complex attribution trend and pattern of climate change to extreme weather conditions for the locations of highly impacted hot spots.

A global event-based human mortality database or databases would help address some fundamental questions: Where are the most vulnerable places prone to the impact of climate change across space and over time? Who are the people affected the most over time? What is the human mortality pattern directly and indirectly associated with climate change over time? A database of human mortality from extreme weather events related to climate change would reveal some regional and global patterns from time series and trend analyses. The event-based mortality will help reveal geospatial and temporal benchmarks and anomalies over time for a given area. It can also help better distinguish a region's mortality rate and rate change from non-climate related causes to those from hazards aggravated by climate change. Furthermore, the database will also provide fundamental information for promoting global environmental resilience, sustainable environmental policies, mitigation strategies, and needed help for the regions with less capacity to deal with the problems.

Remote sensing technology helps with monitoring hazardous events and drastic land use transformation. It has transformed the monitoring process of the spatial and temporal patterns and changes of biological diversity through structural, compositional, and functional measurements of ecosystems [39]. Ground detailed and continuous data collection would allow the science community to combine them with remote sensing data to model the relationship between climate change, environmental hazards, and human mortality. A comprehensive assessment of tropical cyclones over longer periods is currently missing [57]. The integration of analytical techniques and methods with remote sensing data has enhanced image classification for monitoring biodiversity loss, soil erosion, hydrological disturbances, water and solid contamination, global warming and modeling ecological sustainability and future growth and planning [58].

A global event-based human mortality database associated with climate change would be a benchmark for environmental sustainability. The database variables may include the impact zones of tropical storms, extreme precipitation and floods, extreme heat waves and droughts, dust storms, wildfires, abnormal air pollution, etc. The event-based mortality database can be developed from multiple collaborative efforts and sources (Figure 2). Remote sensing data and analysis can be used to monitor and map the spatial extent of impacted areas. Community reports, hospital records, and citizen science inputs would add ground data points. The science community can use remote sensing, ground observations, and historical databases for estimation simulation and projection of the long-term mean death rate of a region. The abnormal rate above the long-term mean death rate would serve as an indicator of climate change-related human mortality. A separate data verification group would assess the accuracy and integrity of data. Then, communication of the data and analysis results would bridge the knowledge gap and disseminate pertinent information to the public to promote better policies and response strategies.

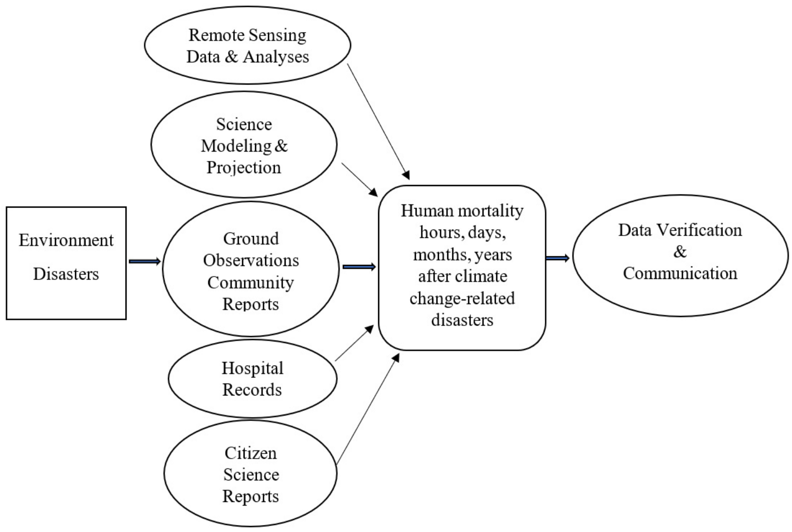

Figure 2. Conceptual framework of climate change-related event-based human mortality database.

6. Communication Strategies on Climate Change

Media and communication processes are central to how many people know about and make sense of our environment and how environmental concerns are generated, elaborated, manipulated, and contested [59]. Framing and communicating climate change is of particular interest in public discourse as communication plays an important role in fostering or inhibiting environmental policy and advocating public behavior changes regarding support and engagement in climate action [60,61]. Climate change exerts complicated, complex, persistent, and accumulative long-term effects on environmental sustainability and human health. Current research has largely focused on identifying the environmental problems and risks associated with climate change. Yet, more efforts are needed to foster the strategy and approach for more close collaboration between science and communication professionals.

An extensive literature review by Huang et al. [62] showed that public health adaptation essentially operates at two levels, namely, adaptive capacity building and implementation of adaptation actions. They proposed that high research priority should be given to multidisciplinary research on assessing potential health impacts of climate change and evaluating cost-effective public health adaptation options. Communicating climate science beyond academia is necessary for enhancing the dissemination of heterogeneous climate knowledge, and social scientific approaches could be effective in relying on science and emphasizing evidence-based advocacy and engagement in the current era of global challenges and uncertainty [63]. Climate change presents social and environmental problems. Thus, communicating the effects of climate change can be a geopolitical issue. There is a consensus among the research community on climate change, but a substantial portion of the world's population remains unaware or unconvinced that human activity is responsible for climate change, with those unaware of the problem in the less economically developed regions or excessive degrees of economic wealth and market liberalism negatively correlated to climate change belief [64]. In the United States, using or avoiding the term climate change may be necessary to maintain audience engagement by different political parties [65]. Communication also plays an important role in finding new pathways to communicate facts and insights from climate change research with stronger sustainability solutions [66].

Communication is important in disseminating information, improving understanding of problems, and promoting common-shared strategies for sustainable solutions. Environmental communication serves a global socioeconomic environment, and research functions in spotting critical issues and areas, promoting cross-disciplinary collaborative research, advocating open communications on concerns and solutions, and promoting sustainable individual actions and public policies to mitigate climate change impacts better. Theoretical and empirical research on the role of the public sphere, civil society and social movements shows that democratic civic engagement is core to successful social change efforts [67].

Accordingly, scholars have long recognized that what is needed is a communications process that promotes civic engagement and dialog [68,69] when people are provided with full information regarding a particular risk and are then included in the development of responses to it. They are much more likely to engage in taking action than if given only limited information or responsibility [70]. One important goal of communication with patients and the public should be to increase understanding of the connections between climate change and health and the actions people can take to protect their health and address the root causes of the problem [71]. Creating a human mortality database where citizens can access information will thus benefit the communication process and subsequent engagement with the community.

7. Conclusions and Discussion

Global urbanization is inevitable. Rapid urban expansion, economic development, and land transformation have strongly and negatively contributed to climate change and environmental sustainability. Consequently, human health and human mortality are affected by acute primary and prolonged accumulative, compound secondary, and tertiary environmental risk factors due to climate change.

The primary impacts of climate change manifest as extreme weather conditions in terms of dramatic changes in temperature, precipitation, and wind speed. The secondary impacts extend the primary impacts into land productivity, food supply shortage and insecurity, terrestrial and marine ecosystems disruption, infrastructure, and resources damage, as well as general economic loss. The tertiary impacts are long-term compound and accumulated effects, such as social instability, geopolitical conflicts, physical and mental diseases, and persistent socioeconomic and ecological stresses.

It is important to track the three-level impact risks. Climate change stems from the changes of major climate forcing and dynamic energy flow between earth and atmosphere systems. Remote sensing technology has demonstrated effectiveness in tracking severe tropical storms, sea surface temperatures and sea level rise, land use and land cover changes, and the melting of polar ice sheets [72,73]. Climate change research analyses global long-term data of the past, present, and future climate systems and other biophysical systems; remote-sensing technologies have been extensively applied to climate change monitoring at various temporal and spatial scales [53,74].

The compound and accumulated primary, secondary, and tertiary impacts of climate change on human mortality are essential to monitoring, understanding, and mitigating climate change damages. The event-based mortality database will provide empirical observation data for reliable geospatial trend and pattern analysis. There is no database on the impacts of past extreme events, which is a major barrier to mitigating future damages [75]. An event-based mortality database will help reveal geospatial variations and hotspots of highly impacted areas of climate change and validate and improve climate model simulations and projections. It is highly feasible to develop the database by combining remote sensing techniques and ground observations.

It is imperative for the global community to set priorities and policies to effectively take on the challenges of climate change on environmental sustainability and human mortality, such as developing an event-based mortality database for any finer-resolution research on climate change and tracking multi-tiered impact risks with different geospatial and temporal dimensions and characteristics. An event-based mortality database and climate change impacts analysis will help refine the delineation of highly impacted areas and regions for targeted resource allocation and mitigation. It is promising to use an ecosystem-based adaptation strategy, including the conservation, restoration, and sustainable management of ecosystems, ecosystem processes, and biodiversity, to address the impacts of climate change [76]. Integrated ecological, technological, and social planning and resources management transition to climate change adaptation presents an opportunity to achieve resilience and sustainability [77–81].

Communicating sustainability, individual actions and behavior were seen as influential [67]. Humans must change our behavior in the near term to mitigate the overall effects of climate change in the long run, and policymakers need to develop environmental policies to motivate and foster individual behavioral change [61]. Communication plays an important role in disseminating scientific information about climate change and the consequences and connection between human mortality and climate change.

Human mortality anomaly is often the signpost for measuring the magnitude and severity of adverse environmental changes. Human activities and economic developments are responsible for rapid climate change and adverse environmental impacts, which, in turn, negatively affect human health and mortality. Human capital is crucial in developing and maintaining a sustainable socioeconomic world. A global event-based human mortality database related to climate change will facilitate better environmental mitigation strategies and policies. Communicating climate change and its impacts on human mortality beyond the science community is important to promote global policies and actions for overall global climate adaptation, resilience, and sustainable economic development.

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