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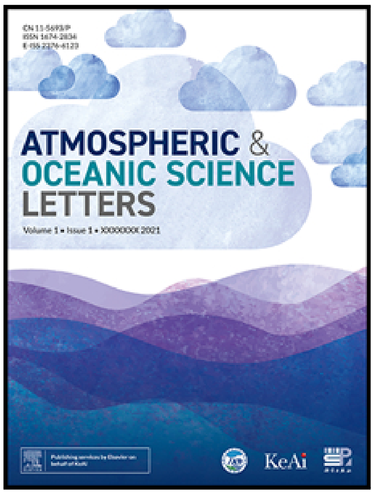

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Compound extreme events and health risks in China: A review

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碳中和

ABSTRACT

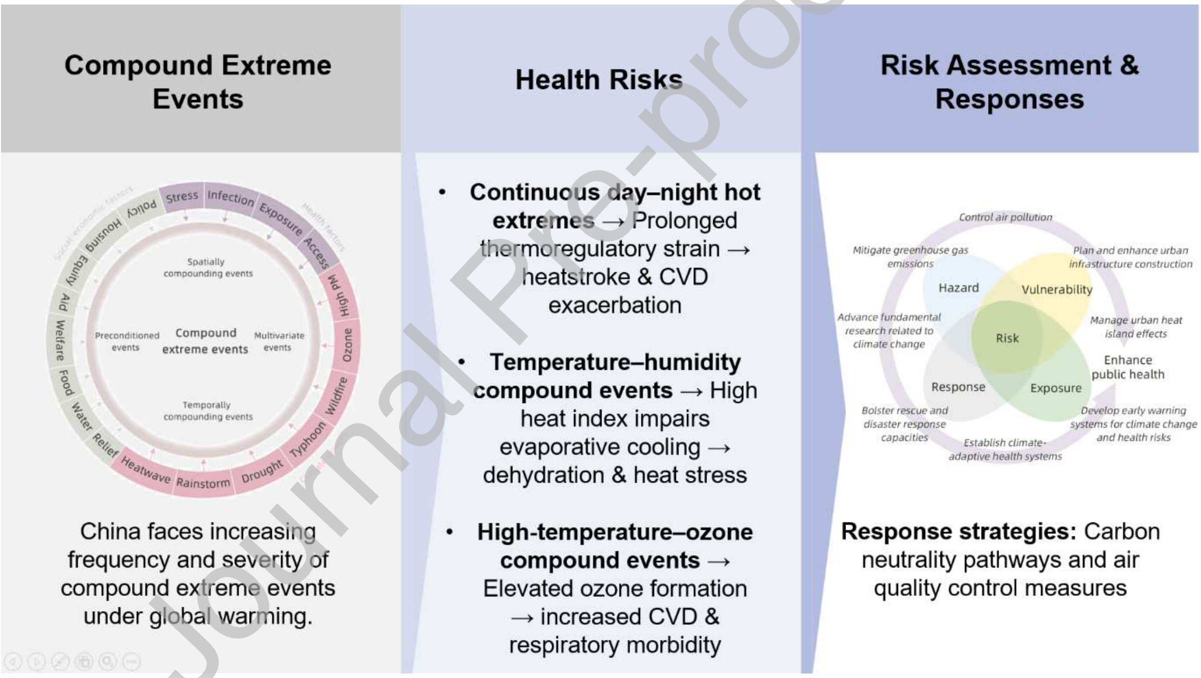
Against the backdrop of global warming, China has been facing increasingly frequent and severe extreme weather and climate events, with a prominent risk of compound extreme events induced by interactions among multiple climate drivers and/or hazards. The present study first reviews the definition and classification of compound extreme events in China. Then, it summarizes research progress on the evolutionary characteristics, formation mechanisms, and future projections of different types of compound extreme events. The potential risks and possible impact pathways of three specific event types—namely, continuous day–night hot extremes, temperature–humidity compound events, and high-temperature–ozone compound events—on the health of the Chinese population are then explored. Finally, a framework for assessing the hazard risk of compound extreme events is constructed, accompanied by response strategies based on carbon neutrality targets. Building on existing research achievements, five future research directions are proposed: (1) identifying the risk chains of compound events; (2) addressing the constraints of observational records and coupled model performances; (3) attributing and understanding the drivers of compound extreme events; (4) finding optimal pathways for carbon reduction and air quality improvement; and (5) promoting inter-disciplinary, multi-regional, and cross-sectoral collaboration. Strengthening research in these directions will deepen our understanding of compound extreme events and provide technological support for climate change adaptation and health risk responses in China.

摘要

在全球变暖的背景下，中国面临着日益频繁和严峻的极端天气气候事件，其中以多种气候驱动因子和/或灾害相互作用而形成的复合型极端事件风险尤为突出。本文首先回顾了中国区域

复合型极端事件的定义与分型；然后综述了不同类型复合型极端事件的演变特征、形成机制以及未来预估等方面的研究进展；随后，探讨了日夜持续型极端高温事件、温湿复合事件以及高温–臭氧复合事件等三类事件对我国人群健康的潜在风险及可能的影响途径；最后，阐述了复合型极端事件灾害风险评估框架，并在此基础上提出了基于碳中和目标的应对策略。在总结既有研究成果的基础上，提出了五个未来亟需关注的研究方向：（1）复合事件灾害风险链的识别问题；（2）观测资料和耦合模式性能的制约问题；（3）复合型极端事件的归因与成因问题；（4）碳减排与空气质量改善的最优路径问题；（5）多学科、多区域、多部门的合作问题。加强上述方向的研究有助于深化对复合型极端事件的理解，并为我国气候变化适应和健康风险应对提供科技支撑。

GRAPHIC ABSTRACT (ONLINE ONLY)



1. Introduction

Over the past century, China's climate has undergone significant changes, primarily driven by global warming. As surface temperature rises, the frequency and magnitude of regional extreme events, such as heatwaves, extreme rainfall, droughts, typhoons, and storm surges, have increased. These events pose significant challenges to public health, ecosystems, food security, and socioeconomic systems. Extreme events are often categorized into weather and climate extremes. Weather extremes are rare meteorological events occurring at specific times and locations, characterized by low statistical probability. In contrast, climate extremes refer to persistent anomalous conditions of meteorological variables over an extended period, potentially leading to extreme seasonal averages or totals (IPCC, 2021). To advance research on extreme events in the context of global warming, the World Meteorological Organization and the World Climate Research Programme established the Expert Team on Climate Change Detection and Indices (ETCCDI). This team has defined 27 representative extreme temperature and precipitation indices based on a unified framework (Zhang et al., 2011), which are widely used in global and regional studies of extreme weather and climate events. Extreme events are typically defined via two approaches: absolute thresholds based on fixed values, and relative thresholds based on percentiles. For example, meteorological operational systems in China define heatwaves as periods where temperatures exceed 35°C for three consecutive days. However, due to the spatiotemporal heterogeneity of climate variables, relative thresholds based on percentiles or parameter estimation methods derived from extreme value theory are preferred for defining extreme events in research.

In recent years, extreme events in China have exhibited new characteristics in three aspects. First, extreme events are becoming more widespread, with high-impact, low-probability events occurring more frequently. The impact of hazards is no longer confined to specific areas but is increasingly affecting broader regions. Second, extreme events occur more suddenly, with a rise in unforeseen incidents and new combinations of hazards that have not occurred before. Third, a discernible trend is emerging towards enhanced extremity in these events, with both the frequency and intensity of extreme events increasing. These emerging characteristics have negatively impacted livelihoods, economic development, and social equity in China. Moreover, they present significant challenges for meteorological hazard risk management, emergency responses, and climate adaptation strategies. Compared to extreme events triggered by a single driver, the simultaneous or consecutive occurrence of two or more extreme events often results in more severe social and environmental consequences. This phenomenon, where multiple climate drivers and/or hazards combine to create social or environmental risks, is defined as compound extreme events. These have evolved into frontier issues and major scientific challenges in the field of climate change research (Zscheischler et al., 2018; Yu et al., 2023).

As urbanization and industrialization rapidly advance in China, air pollution has emerged as the significant environmental problem and major health threat to residents (Zheng et al., 2023). To address these issues, the Chinese government has implemented various regulatory measures, such as the first 5-year Clean Air Action and Blue Sky Protection Campaign Plan since 2013. These efforts have led to significant reductions in $PM_{2.5}$ pollution, although levels still fall short of high standards set by the World Health Organization (Xue et al., 2019). However, the near-surface ozone concentrations in eastern China remain high during the warm season, with an increasing frequency of persistent ozone pollution events. This has emerged as the primary factor influencing the summer air quality in China. Ozone, classified as a secondary pollutant, primarily forms through photochemical reactions involving precursors such as volatile organic compounds, carbon monoxide, and nitrogen oxides. In densely populated eastern China, the heavy dependence on fossil fuels and biofuels for heating and transportation has resulted in a rapid surge in emissions of ozone precursors. This not only elevates ozone concentrations but also catalyzes the formation of photochemical smog, posing serious threats to public health, ecosystems, and agricultural production.

In recent years, review articles on compound extreme events have discussed their observational characteristics and underlying drivers (Zscheischler et al., 2020; Hao and Chen, 2024). However, there remains a gap in coverage concerning the impacts of these events, particularly on health risks, and few reviews have involved the interaction of extreme weather and air pollution. Therefore, a more comprehensive synthesis of research progress in this field is warranted. This paper focuses on the spatiotemporal evolutionary characteristics of typical compound extreme events in China and their implications for human health. The rest of the paper is structured as follows: section 2 summarizes the definition, evolutionary characteristics, and driving mechanisms of compound extreme events; section 3 outlines the adverse effects of three typical compound extreme events on the population health in China; section 4 describes the development of a hazard risk assessment framework of compound extreme events and proposes corresponding countermeasures; and section 5 presents a summary and outlook.

2. Compound extreme events under global warming

Since the Intergovernmental Panel on Climate Change (IPCC) first introduced the concept of compound extreme events in 2012, the academic community has made significant progress on the definition, evolutionary characteristics, and driving mechanisms of this phenomenon over the past decade. This section reviews the major advancements in this field.

2.1. Definition and characteristics

Research on extreme weather and climate events has a long history, but the focus on compound extreme events is relatively recent. In February 2012, the IPCC introduced the concept of compound extreme events in its special report entitled "Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation" (SREX) (IPCC, 2012). Since then, the academic community has worked to refine this framework and deepen its understanding. Leonard et al. (2014) defined compound extreme events as combinations of multiple variables or events that interact to produce extreme impacts. In the IPCC's Sixth Assessment Report, compound events were given dedicated attention in a separate chapter. These events were categorized into four types based on the relationships between different factors: preconditioned, multivariate, temporally compounding, and spatially compounding events (Fig. 1). Preconditioned events occur when prior meteorological or climatic conditions, such as saturated soils, influence subsequent extremes like heavy rainfall. Multivariate events involve simultaneous extremes, such as the co-occurrence of droughts and heatwaves. Temporally compounding events involve successive hazards, such as tropical cyclones following one another. Spatially compounding events refer to multiple extremes affecting different locations but with shared consequences, such as simultaneous heatwaves disrupting global food production (Table 1). However, ambiguity remains in this classification, as some events do not fit neatly into a single category. Many compound extreme events exhibit characteristics of multiple categories, blurring the lines between them.

Research on compound extreme events has evolved through several key stages, marked by a gradual shift in focus. Initially, the emphasis was on defining different types of compound events and analyzing their spatiotemporal evolution. As research advanced, researchers shifted from examining characteristics to exploring the underlying mechanisms driving these events. Utilizing extensive observational data and advanced numerical models, they have investigated the complex interactions between various factors contributing to compound events, while also projecting how these events might change in a warming climate. Despite the community's recognition of the importance of societal, economic, and ecological impacts (a bottom-up approach) in studying compound extreme events, formal research often relies on predefined thresholds assumed to have significant effects (a top-down approach). This reliance is largely due to the challenges of accessing raw data on casualties, crop losses, and other economic consequences.

2.2. Historical and future trends

2.2.1. Preconditioned events

Weather whiplash events are characterized by abrupt transitions between two opposite and persistent large-scale circulation states, such as a shift from drought to flooding or from cold snaps to heatwaves. These events can be classified as either temporally compounding or preconditioned, depending on the perspective. A notable case of weather whiplash events occurred in the North China Plain during summer 2024. After a severe spring meteorological drought, the region quickly shifted to flooding in early July (Ding et al., 2025). The July rainfall represented the highest value observed over the past half century, triggering geological hazards such as flash floods and debris flows. The causes of such events can be traced to prolonged drought-induced soil desiccation and cracking, which results in soil loosening and reduces its flood resistance. When heavy rainfall follows, the dry soil is unable to absorb and retain moisture effectively, and the scouring effect of rainfall further erodes the weakened soil structure, increasing the likelihood of landslides, debris flows, and other geological hazards. Additionally, long-term drought may lead to vegetation die-off, weakening the ability of plants to retain soil and slow water flow, which further elevates the risk of these hazards (AghaKouchak et al., 2020). Chen et al. (2020) indicated that most regions in China experienced at least one drought–flood compound event from 1975 to 2004. The frequency and intensity of these events are expected to increase, particularly in the North China Plain. Fang and Lu (2023) reported a significant rise in weather whiplash events, characterized by abrupt transitions between wet conditions and warm–dry periods, during historical observations. Under high-emission scenarios, climate warming is projected to amplify the likelihood of such events by 2 to 3.5 times by the end of the 21st century, with the East Asian monsoon region being especially vulnerable (Tan et al., 2023).

2.2.2. Multivariate events

Due to the negative correlation between seasonal mean temperature anomalies and seasonal total precipitation anomalies, heatwaves and droughts (including meteorological, agricultural, and hydrological droughts) often occur simultaneously during warm seasons (Peng et al., 2023). This concurrent occurrence forms compound hot–dry extreme events, which have been extensively studied. Research indicates that the frequency, intensity, and duration of compound hot–dry events in China have significantly increased over the past 60 years, with a gradual expansion of their spatial impact and a notable rise in population exposure (Hao, 2022). These compound hot–dry events are projected to continue increasing in China, particularly in eastern regions. Another widely studied type of compound event is the warm–humid compound event, characterized by extreme levels of both temperature and humidity occurring simultaneously. The frequency of these events has significantly increased across most of China during summer, particularly in western and northern regions. Notably, humidity anomalies have been found to play a crucial role in the variation of compound warm–humid events, surpassing the impact of temperature anomalies in certain regions (He and Chen, 2023). Under global warming, projections based on the Wet Bulb Globe Temperature (WBGT) metric suggest that by the 2040s, summer heat and humidity levels across nearly all of China will be comparable to the most intense historical warm–humid events (Li et al., 2020).

High-temperature–ozone compound events occur when elevated temperatures coincide with ozone pollution. Xiao et al. (2022) observed a significant increase in the frequency of such events in China from 2013 to 2020, particularly in the Beijing–Tianjin–Hebei and Yangtze River Delta regions. Under future high-emission scenarios, projections indicate that the number of annual global high-temperature–ozone compound event days could increase by approximately 35 days by the end of the century, leading to a corresponding rise in population exposure (Ban et al., 2022). In China, despite expected reductions in near-surface ozone levels due to emission control measures, high-temperature–ozone compound events are still projected to increase, driven by rising temperatures.

Atmospheric drought (low atmospheric water vapor) and soil drought (low soil moisture) overlap to form compound drought events, which can harm ecosystem productivity and terrestrial carbon absorption. Historically, human-induced reductions in soil–atmosphere compound drought frequency have been attributed to aerosol-driven cooling offsetting the effects of rising greenhouse gas concentrations (Zeng et al., 2023). However, projections indicate an increase in the frequency of these events throughout the 21st century (Zhou et al., 2019).

Flood hazards in coastal areas can arise from a variety of sources, including coastal floods driven by extreme sea levels, pluvial floods from heavy rainfall, and fluvial floods caused by river overflow. When multiple types of flooding occur together, they create compound flood events (Saulnier et al., 2017; Xu et al., 2022). A notable example is Typhoon Mangkhut in September 2018, which hit Guangdong Province and caused strong winds, massive tidal waves, storm surges, and heavy rainfall. This combination led to multiple types of floods occurring simultaneously, resulting in significant economic losses for coastal cities. The risk of compound flooding is expected to rise due to factors such as sea level rise, stronger storms, increased rainfall, and changes in land use and cover types (Zhang et al., 2021a). Under high-emission scenarios, the probability of compound flooding events could increase by more than 25% by the end of this century (Bevacqua et al., 2020). In addition to flood risks, wind–rain compound events, where strong winds and heavy rainfall occur together, are becoming more frequent. Zhang et al. (2021b) reported a rise in these events in China between 2011 and 2018, with projections of further increases in frequency, particularly in southeastern coastal regions (Meng et al., 2023). Moreover, compound extreme events are also intensifying in marginal seas of China. Burger et al. (2022) found that sustained carbon dioxide emissions have significantly increased the frequency of compound marine heatwave and ocean acidification events. With a global temperature rise of 2°C above pre-industrial levels, the number of days experiencing such compound marine extremes is projected to increase by 22 times.

2.2.3. Temporally compounding events

Continuous day–night hot extremes are defined as periods when temperatures significantly exceed high-end thresholds over consecutive day–night cycles. Wang et al. (2020a) found that the frequency and intensity of summer continuous day–night hot extremes in the Northern Hemisphere have notably increased since 1960. Using observational constraints for future projections, they further found that the types of high-temperature events in the Northern Hemisphere have gradually shifted from daytime extremes to nighttime and continuous day–night hot extremes. In China, high-emission scenario projections indicate substantial exposure to these extremes in major urban areas. By 2050 (2090), 2050 (2070), and 2030 (2050), it is anticipated that 50% (100%) of the land area in the Beijing–Tianjin–Hebei, Yangtze River Delta, and Pearl River Delta regions will be consistently exposed to continuous day–night hot extremes. By the end of this century, the populations exposed to these extremes in these three major urban areas are projected to increase by nearly 7 million, 9 million, and 6 million, respectively (Wang et al., 2020b; Xie et al., 2022).

Flood–heat compound events refer to the occurrence of floods and heatwaves in succession within a relatively short period. Severe flooding can disrupt water and power supplies, rendering cooling equipment unusable during subsequent hot weather and increasing health risks posed by high temperatures. Chen et al. (2021) indicated that extreme rainfall-induced flooding and heatwaves rarely occurred consecutively within a week in China in the past. However, since 2000, the likelihood of such events has increased by 5 to 10 times in southern, northwestern, and northeastern China. With continued climate warming, this probability is expected to rise further, particularly in densely populated southeastern China (Liao et al., 2021).

Multiple tropical cyclone events can pose a serious threat to coastal areas of China, characterized by the occurrence of two or more tropical cyclones within the same ocean basin over a short period. In the Northwest Pacific, this phenomenon is also referred to as a multi-typhoon event. Compared to individual tropical cyclones, these events can result in more extreme rainfall, stronger winds, and heightened storm surge hazards, presenting significant challenges for operational forecasting (Schenkel, 2016). Since the mid-20th century, the frequency of tropical cyclone group events in the Northwest Pacific has declined significantly, a trend that is expected to persist under future warming (Fu et al., 2023).

2.2.4. Spatially compounding events

Research on spatially compounding extreme events in China remains limited. One notable event occurred between June and July 2020, when the middle and lower reaches of the Yangtze River basin experienced a record-breaking Meiyu season, lasting 62 days and setting a new record for total precipitation. At the same time, southern China faced unprecedented heatwaves (Ye and Qian, 2021). Wang et al. (2023) employed the storyline attribution method to construct circulation-analog scenarios and examine the event. They found that human-induced atmospheric warming and moistening contributed to a 6.5% increase in total precipitation during the summer 2020 event, while also intensifying the concurrent heatwave in southern China by approximately 1°C. Under a moderate future emission scenario, similar large-scale atmospheric circulation patterns by the end of the century could lead to a 14% increase in extreme rainfall intensity and a 2.1-fold amplification of heatwaves in southern China. In the summer of 2021, a record-breaking marine heatwave affected a vast area of the subtropical Northwest Pacific, coinciding with extreme terrestrial heatwaves in Northeast Asia, including northeastern China. Tang et al. (2023) applied the optimal fingerprinting method to isolate anthropogenic signals and correct biases in the latest Coupled Model Intercomparison Project models. They showed that human-induced global warming has increased the likelihood of 2021-like spatially compound marine and terrestrial heatwave events by about 30 times. Even under a moderate future emission scenario, the risk of similar events in the second half of the 21st century is projected to be at least six times higher than in the 2020s.

Southwest China has experienced frequent spatially compounding droughts, where multiple provinces (e.g., Yunnan, Guizhou, Guangxi) are simultaneously affected by prolonged water deficits (Wang et al., 2024). A notable case is the 2009–2010 mega-drought, one of the worst in recorded history, which impacted over 60 million people, caused severe crop failures, drinking water shortages, and economic losses exceeding US$2.8 billion. Previous studies attributed these events to persistent La Niña–like sea surface temperature anomalies, weakened southwesterly moisture transport, and enhanced subtropical high pressure over southern China. Climate projections suggest that under continued warming, the frequency and spatial extent of such compound droughts are likely to increase, exacerbating risks to agriculture, water security, and ecosystems in the region (Wang et al., 2015).

2.3. Driving mechanisms

2.3.1. Large-scale atmospheric circulation

The formation and persistence of anomalous high-pressure systems are crucial in driving local heatwave–drought compound events. These systems feature sinking air, which causes adiabatic warming and significantly raises surface temperatures. The downward motion also reduces cloud cover, allowing more solar radiation to reach the surface, further intensifying the heatwave. Simultaneously, high-pressure systems lead to decreased precipitation, worsening drought conditions by reducing soil moisture. Widespread high-pressure anomalies can influence both the temporal and spatial distribution of heatwaves or droughts, causing originally independent extreme weather events to overlap, resulting in more prolonged or widespread compound events. Kornhuber et al. (2020) indicated that quasi-stationary Rossby waves in midlatitudes can trigger heatwaves in major crop-producing areas, posing food security risks. Tang et al. (2023) identified midlatitude anticyclonic high-pressure systems, induced by the Pacific–Japan teleconnection, as key drivers of compound marine and terrestrial heatwaves across the Northwest Pacific during the summer of 2021.

In addition to high-pressure systems, the westerly belt in the upper troposphere can serve as a key linkage between different components of compound extreme events. For example, in September 2021, simultaneous record-breaking rainfall occurred in northern China and northwestern India. Na and Lu (2022) suggested that the Silk Road teleconnection pattern, propagating along midlatitude westerly jet streams, played a crucial role in these events. Similarly, during the summer of 2022, unprecedented heatwaves and flooding impacted the Yangtze River Basin in China and western Pakistan. He et al. (2023) highlighted that in El Niño decaying years, elevated tropical tropospheric temperatures and unusually strong westerly winds over the Qinghai–Tibet Plateau could induce anomalous sinking (lifting) motion on the east (west) side of the plateau, triggering spatially compound heatwave–flooding events.

Large-scale atmospheric circulation anomalies are closely tied to internal climate variabilities such as the El Niño–Southern Oscillation (ENSO), Indian Ocean Dipole, Pacific Decadal Oscillation, and Madden–Julian Oscillation. ENSO, the most significant interannual ocean–atmosphere variability, exerts a profound influence on global weather patterns through its teleconnections, affecting regions both within and beyond the tropics (Hu et al., 2021; Singh et al., 2022). It plays a crucial role in shaping the spatial distribution of summer droughts and floods in China. During El Niño decaying years, a stronger and more southward Northwest Pacific subtropical high transports moisture from the tropical ocean to the Yangtze River basin, causing frequent flooding. Meanwhile, other regions, including North China, the Yellow River basin, and southwestern China, experience reduced rainfall and more frequent heatwaves (Huang et al., 2004; Tang et al., 2021).

ENSO also affects tropical cyclone cluster events by triggering circulation anomalies. For example, seven tropical cyclones, including five typhoons, developed consecutively in the Northwest Pacific between 6 August and 10 September 2004. Hu et al. (2018) linked this cluster to an El Niño Modoki–like mode and anomalous cooling in the Indian Ocean, which triggered a monsoon trough over the Northwest Pacific. The first strong typhoon emitted Rossby wave packet energy into the monsoon trough, facilitating the development of subsequent cyclonic disturbances and resulting in a temporally compound tropical cyclone cluster event (Fig. 2).

2.3.2. Land–atmosphere interaction

The spatiotemporal evolution of soil moisture and temperature, along with other land surface variables, significantly influences the occurrence and development of compound heatwave–drought events at regional scales through land–atmosphere coupling dynamics. Soil moisture, a critical component of the surface water cycle, plays a vital role in heat flux exchanges between the land and atmosphere (Seneviratne et al., 2010; Miralles et al., 2019). As soil moisture decreases, local evapotranspiration diminishes, leading to reduced upward latent heat flux and an increase in sensible heat flux, which warms the atmosphere. This warming elevates saturated water vapor pressure, hindering the condensation of water vapor into precipitation and sustaining drought conditions. Additionally, rising near-surface air temperatures intensify evapotranspiration, further depleting soil moisture and creating a positive feedback between high temperatures and soil drought.

Human activities significantly influence the occurrence and development of compound extreme events through changes in land use and land cover, which affect surface albedo, heat, momentum, and substance exchanges between land and atmosphere. Rapid urbanization in China over the past four decades has notably increased the frequency and intensity of extreme heat events in urban areas, primarily due to the urban heat island effect (Luo and Lau, 2018). To evaluate the contributions of large-scale factors, such as greenhouse gas emissions, and local factors, such as urbanization, to the rise in continuous day–night hot extremes, Wang et al. (2021) developed an attribution framework that integrates the impacts of these external forcing factors across various spatial and temporal scales. Their findings indicate that greenhouse gas emissions are the primary driver of increased continuous day–night hot extremes in eastern urban areas of China, with urbanization accounting for approximately one-third of this increase.

The spread of impermeable surfaces, such as asphalt roads and concrete buildings in urban areas, impedes heat dissipation through soil and vegetation evapotranspiration during the day, leading to heat accumulation. At night, cities release this accumulated heat, further elevating atmospheric temperatures. This transformation in land use and land cover due to urbanization is a significant factor in the formation of continuous day–night hot extremes (Wang et al., 2020a). Alongside the urban heat island effect is the urban dry island effect, which suppresses near-surface moisture evaporation, decreases atmospheric relative humidity, and enhances stability. This combination contributes to the concentration of urban pollutants in the boundary layer, creating conditions conducive to compound atmospheric pollution hazards. Additionally, increased atmospheric aridity raises sensible heat flux, further exacerbating the urban heat island effect.

Beyond urbanization, large-scale agricultural activities in various river basins in China, characterized by deforestation and vegetation destruction, have led to severe soil erosion. These ongoing changes in land use have reshaped the original land and vegetation cover structure. Soil devoid of vegetation protection becomes more prone to erosion during heavy rainfall, heightening the risk of compound hazards such as debris flows.

2.3.3. Self-propagation mechanism

Extreme weather events in upstream regions can profoundly influence downstream weather systems through various mechanisms, including atmospheric circulation responses and non-local land–atmosphere interactions. For instance, prolonged droughts in upwind areas can affect rainfall, temperature, and wind speed in downwind regions, ultimately affecting downwind water resources and agricultural production. Specifically, local droughts reduce near-surface humidity, which extends into the troposphere through vertical mixing processes, leading to decreased water vapor content in downstream areas. Under similar precipitation efficiency conditions, this reduction can result in lower rainfall downstream, exacerbating drought conditions. Additionally, decreased water vapor can weaken uplift motion, further diminishing convective rainfall (Schumacher et al., 2022).

Beyond the potential self-propagation of drought, extreme rainfall events upstream can release large volumes of rainwater into river systems over a short period, resulting in upstream peaks. This surge of water then flows downstream through river channels, triggering floods via hydrological processes (Tao et al., 2023). Furthermore, atmospheric pollutants carried by winds can disperse and drift downwind, affecting not only nearby areas but also regions far from the pollution sources, thereby exacerbating environmental challenges across multiple regions.

3. Health implications of compound extreme events

Research on the health impacts of compound extreme events mainly adopts an environmental epidemiological perspective, using time-series, case-crossover and cohort designs to quantify relationship between exposure to these events and the ensuing mortality or morbidity in individuals or populations (Ebi et al., 2021). This section reviews the adverse health effects of three typical types of compound extreme events on the population health in China.

3.1. Continuous day–night hot extremes

Extreme heatwaves pose a serious threat to human health, leading to acute conditions such as heatstroke and heat-related illnesses, as well as chronic diseases like cardiovascular, respiratory, urinary, and neurological disorders (Huang et al., 2012; Chen et al., 2022). For instance, a study of five major Chinese cities found that exposure to extreme heat at the 99th percentile, compared to the 90th percentile, increased mortality from ischemic heart disease by 18% (Guo et al., 2013). Beyond short-term heat exposure, intra-day, diurnal, seasonal, and interannual temperature variability also present additional health challenges (Kang et al., 2020). A nationwide cohort study on hypertension revealed that each 1°C increase in daily temperature variability raised the risks of all-cause mortality, cardiovascular disease, and stroke by 13%, 12%, and 9%, respectively (Tang et al., 2022). Similarly, long-term temperature variability was linked to a 6% higher risk of cardiovascular diseases, a 7% increase in coronary heart disease, and a 3% rise in stroke rates in China (Kang et al., 2021).

Previous studies have examined the health risks associated with extreme heat. Building upon this, Wang et al. (2021) explored the effects of continuous day–night hot extremes on non-accidental deaths in nine southern provinces and municipalities in China using a mortality risk attribution model. Their findings revealed that each additional day of continuous hot extremes raised the risk of non-accidental deaths by 15%. Vulnerability varied among different groups, with elderly individuals and women showing greater susceptibility to these conditions. Compared to single daytime or nighttime heat events, continuous day–night hot extremes posed a significantly higher health risk. He et al. (2021) further projected that deaths attributed to these prolonged heat events could increase 7 to 19 times by the end of the

21st century under moderate and high emission scenarios, respectively.

Biological studies have elucidated that exposure to high temperatures could trigger thermoregulatory mechanisms coordinated through neural and humoral pathways, resulting in increased sweat secretion. The loss of inorganic salt ions in sweat leads to increased blood concentration, reduced blood flow to visceral organs, and an accelerated heart rate, raising blood pressure and increasing cardiovascular strain, which may contribute to cardiovascular diseases. Moreover, continuous day–night hot extremes may exert negative effects on human health through a dual-pressure mechanism. Nighttime high temperatures may disrupt sleep patterns, hindering the body's repair and adjustment processes. Subsequently, during the hot daytime, the body faces another round of stress, potentially weakening the immune system and affecting cardiovascular health (Li et al., 2021).

3.2. Temperature–humidity compound events

Ambient humidity plays a crucial role in modulating the health impacts of extreme temperatures, as the combination of heat and humidity can intensify the body's heat stress and affect hydration. Composite indices such as WBGT, Apparent Temperature, Humidex, and Heat Stress Index have been used to assess the combined effects of temperature and humidity on public health (Fischer et al., 2013). However, these indices often struggle to separate the individual or interactive effects of temperature and humidity on health risks. As a result, some studies define temperature–humidity compound events using specific percentiles as thresholds and analyze their health effects accordingly (Liang et al., 2023).

Fang et al. (2023) found that the risk of non-accidental deaths associated with dry–heat events is significantly higher than that of humid–heat events, with high temperature–low humidity events having a greater impact than individual events combined. In humid conditions, the body's ability to cool through sweating is reduced, raising core body temperature and increasing the risk of heat-related illnesses like heatstroke and heat exhaustion, especially among outdoor workers, the elderly, and vulnerable groups with cardiovascular diseases. On the other hand, low-humidity environments can dry out respiratory mucous membranes, increasing vulnerability to infections and exacerbating weather-sensitive diseases (Zeng et al., 2017).

3.3. High-temperature–ozone compound events

The health impact of air pollution involves several facets, including temporal evolution, chemical composition, particle size, and population vulnerability. When combined with extreme weather events, these effects become more complex, particularly during high-temperature–ozone compound events (Analitis et al., 2014). High temperatures contribute to ozone formation and accumulation, worsening the impact of high temperatures and leading to deteriorating air quality. During heatwaves, atmospheric anticyclones typically accompany low wind speeds and stagnant air, allowing ozone precursors to build up in the atmospheric boundary layer. Clear skies and intense solar radiation further accelerate photochemical reactions, exacerbating near-surface ozone pollution. Additionally, heatwaves can trigger widespread drought, reducing vegetation transpiration and ozone absorption, which leaves more ozone suspended in the atmosphere (Lu et al., 2019).

Previous studies have focused on the independent effects of high temperature or ozone events on population health. However, recent research has begun to explore the modifying effects of temperature on the relationship between ozone and health outcomes. For example, Shi et al. (2020) conducted a time-series study using mortality data from 128 counties in China between 2013 and 2018, finding that high temperatures significantly intensified the ozone–mortality association. In high-temperature conditions, a 10 μg m^{-3} increase in ozone concentration led to increases of 0.44%, 0.42%, and 0.50% in non-accidental, cardiovascular, and respiratory mortality, respectively. Similarly, Xu et al. (2023) analyzed over 500 000 cardiovascular deaths in Jiangsu Province from 2015 to 2021 and found that simultaneous exposure to ozone and heatwaves significantly elevated cardiovascular mortality risk, with the effect becoming more pronounced at higher ozone levels, temperature thresholds, and longer heatwave durations.

The biological mechanisms underlying the health impacts of high-temperature–ozone compound events are complex and multifaceted. First, in hot conditions, residents may open windows to cool indoor spaces, increasing their exposure to outdoor air pollutants. Second, high temperatures place additional burden on the cardiopulmonary system, leading to deeper and faster breathing, which can result in the inhalation of more pollutants. Additionally, both high temperatures and ozone can affect the cardiovascular system through mechanisms such as autonomic nervous system dysfunction, oxidative stress, inflammation, and vascular endothelial damage. These physiological responses can exacerbate the cardiovascular burden, thereby increasing the risk of related diseases.

4. Response to compound extreme events

The growing instability of the climate system has impeded the capability of communities, especially frontline communities, to cope with compound extreme events. This section provides an overview of the hazard risk assessment framework for such events and explores effective strategies for mitigating risks and improving response efforts.

4.1. Risk assessment framework

The impact of compound extreme events depends not only on the severity of events but also on the vulnerability, exposure, adaptability, and emergency management of affected entities. The IPCC identifies four key elements of disaster risk: hazard, vulnerability, exposure, and response, which interact dynamically to shape the scale and scope of impacts (Fig. 3). Hazard includes both natural and human-induced compound events that threaten society, economy, and ecosystems. Vulnerability reflects the susceptibility of affected entities to damage and their ability to adapt or defend against impacts. Exposure measures how much a community is at risk, such as coastal cities in China facing typhoon-induced storm surges. Response refers to the capacity of society, governments, and individuals to react to and recover from disasters. Together, these elements form a comprehensive framework for assessing and addressing the risks posed by compound extreme events.

4.2. Strategies to deal with compound disaster risks

At the 75th session of the United Nations General Assembly, China committed to strengthening its nationally determined contributions, aiming to peak carbon dioxide emissions before 2030 and achieve carbon neutrality by 2060. This dual-carbon goal is crucial for mitigating greenhouse gas emissions and curbing the rise of compound extreme events. Achieving this requires adjusting industrial structures, transitioning to low-carbon energy, improving energy efficiency, and engaging the public in low-carbon practices. On the carbon sequestration side, increasing forest and ocean carbon sinks, along with developing carbon capture technologies, will help balance the carbon cycle and reduce net emissions.

The dual-carbon goal emphasizes the importance of green, low-carbon development and highlights the need for coordinated efforts in climate change mitigation and air pollution control, as both issues stem from the same sources. Reducing carbon emissions not only addresses climate change but also improves air quality. As China progresses toward carbon neutrality, integrating public health into policy design is essential, ensuring that health benefits guide decision-making for dual-coordinated strategies.

In addition to cutting emissions and controlling pollution, enhancing the resilience and adaptability of vulnerable communities is vital for reducing the risk of compound extreme events. Governments can enhance urban infrastructure to build climate-resilient cities, address urban heat island effects, and implement early warning systems for climate and health risks. Establishing climate-adaptive health systems, improving emergency response capabilities, and advancing fundamental climate research are also crucial steps in narrowing the knowledge gap and supporting informed government decision-making (Fig. 3).

5. Summary and outlook

Against the backdrop of urbanization and climate warming, China has experienced a steady rise in the frequency, intensity, and duration of compound extreme events. Drawing on a decade of research on typical regional events, this study first defines and classifies compound events. It then reviews the evolutionary characteristics, driving mechanisms, and future projections of various compound events. Additionally, it explores the potential health risks and impact pathways associated with three major types of compound events. Finally, the study presents a framework for assessing the hazard risks of compound events and provides corresponding response strategies. Despite notable progress, several key facets still require further investigation:

(1) Identifying the risk chains of compound events. Current research on compound extreme events mainly focuses on the interaction between two types of events. However, as climate warming intensifies, future compound events may involve a broader spectrum of extreme events (Reichstein et al., 2021). For example, heatwaves could exacerbate droughts, leading to increased wildfires and dust storms, which further raise air pollutant concentrations and heighten the risk of cardiovascular and respiratory diseases (Reid et al., 2016). The complexity of these hazard risk chains makes their identification challenging. Thus, more research is needed to understand the interactions and cascading effects of various extreme events. Developing models to assess the risks and impacts of compound events will deepen our understanding of how these events interact with vulnerable populations and risk responses.

(2) Addressing the constraints of observational records and coupled model performances. Studying compound extreme events requires a larger sample size than single extreme events. However, the limited duration of meteorological observation records in China, along with data quality concerns in some regions, hampers comprehensive research. Besides, compound extreme events often involve intricate interactions among multiple mechanisms, particularly between extreme weather and air pollution. Current coupled models struggle to accurately simulate these interactions, limiting the ability to predict compound events on subseasonal to seasonal timescales. Calibrating the various drivers of these events is further complicated by their interdependencies. To improve simulation accuracy and better capture these

relationships, efforts should focus on refining and advancing current climate models. The development of the Earth System Science Numerical Simulator Facility in China, known as "EarthLab", will play a crucial role in this progress.

(3) Attributing and understanding the drivers of compound extreme events. The field of extreme event attribution has emerged to quantitatively assess whether and to what extent anthropogenic climate change has influenced the frequency or intensity of specific events. While current research predominantly focuses on single-variable events, there is limited work on attributing compound extreme events. Moreover, significant gaps remain in understanding how internal variability and external forcing influence the dynamic and thermodynamic processes driving these compound events. Addressing these gaps will shed light on the dynamic evolution of compound disaster risks across multiple spatiotemporal scales.

(4) Finding optimal pathways for carbon reduction and air quality improvement. While China has made significant progress toward its carbon neutrality goals, future challenges lie in identifying strategies that can simultaneously reduce carbon emissions and improve air quality, thereby lowering the frequency of compound extreme events. The rapid advancement of big data and artificial intelligence provides enhanced data collection and analysis capabilities, facilitating the development of integrated strategies that align climate change mitigation with air pollution control, ultimately supporting the achievement of carbon neutrality.

(5) Promoting inter-disciplinary, multi-regional, and cross-sectoral collaboration. Understanding compound extreme events requires collaboration across various disciplines, enabling the integration of diverse insights. Given China's vast territory, significant regional

disparities in compound disaster risks add complexity to research, making it challenging to reconcile findings and establish a unified theoretical framework across different regions. Moreover, responding to these events involves multiple governmental departments. To enhance governance systems capable of addressing compound extreme events, it is essential to improve information sharing, foster collaboration, and establish effective communication channels among all stakeholders.

In summary, given the complexity and interdisciplinary nature of compound extreme events, there is an urgent need for more research on regional compound events and their implications within the context of global warming. Such endeavors will lay the groundwork for developing advanced monitoring and warning systems for extreme weather events. Additionally, these insights will guide the development of robust response strategies, ultimately mitigating the adverse effects of compound extreme events on society and populations.

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Competing interests

The authors have no competing interests, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

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Table 1. Examples of four categories of compound extreme events in China.

Category	Event	Date (timescale)	Driver	Impact	Future projection
Preconditioned event	Spring drought followed by record flash-flooding in the North China Plain	Apr–Jul 2024	• Abrupt northward shift of WPSH in early July • A transverse trough causing sustained low-level moisture convergence and heavy rainfall (Ding et al., 2025)	• Agriculture: ~200,000 hectares of crops damaged and ~1.29 million people affected. • Economic loss: 1.46 billion CNY.	Climate model ensembles project a 2.56 ± 0.16-fold increase in precipitation whiplash events by 2100 due to enhanced moisture loading and variability (Tan et al., 2023).
Multivariate event	Compound heatwave–drought in the Yangtze River basin	Jul–Aug 2022	• Persistent subtropical ridge over East China (Liu et al., 2023) • Soil moisture deficits heating and drying the atmosphere (Chen et al., 2025)	• Agriculture: 4.2M ha cropland losses. • Hydrology: River flow reduced by 20–40%, heat stress on 80M people.	Projections indicate an increase in frequency and intensity of concurrent heat–drought extremes under SSP2-4.5 by century's end (Chen et al., 2024).
Temporally	Clustered tropical	6 Aug–10	• El Niño Modoki–like SST	• TCs: Five landfalls (e.g.,	Climate projections (CMIP6) suggest a

compounding event	cyclones (TCs) making successive landfalls	Sep 2004	anomalies in the Pacific (Hu et al., 2018) • Anomalous cooling in the western Indian Ocean modulating monsoon trough position (Hu et al., 2018)	Chaba, Songda) in China and Japan. • Damage: US$4.5B loss, 200+ deaths, coastal infrastructure destroyed.	modest decline in future multiple tropical cyclone events over the western North Pacific (Fu et al., 2023).
Spatially compounding event	Concurrent Mei-yu floods (Yangtze) and heatwaves (South China)	Jun–Jul 2020	• Exceptional warming of the tropical Indian Ocean and enhanced Western Pacific subtropical high (Zhou et al., 2021) • Reduced Arctic sea-ice promoting North Asian blocking (Chen et al., 2022)	• Floods: 219 deaths, US$32B loss, 443 rivers flooded. • Heatwaves: 71 stations with +6°C anomalies, 40 cities broke records.	Under a moderate-emission pathway (SSP2-4.5), similar rainfall extremes could intensify by ~14 %, while heatwave may amplify by ~2.1 °C by 2100, assuming an identical dynamic setup (Wang et al., 2023).

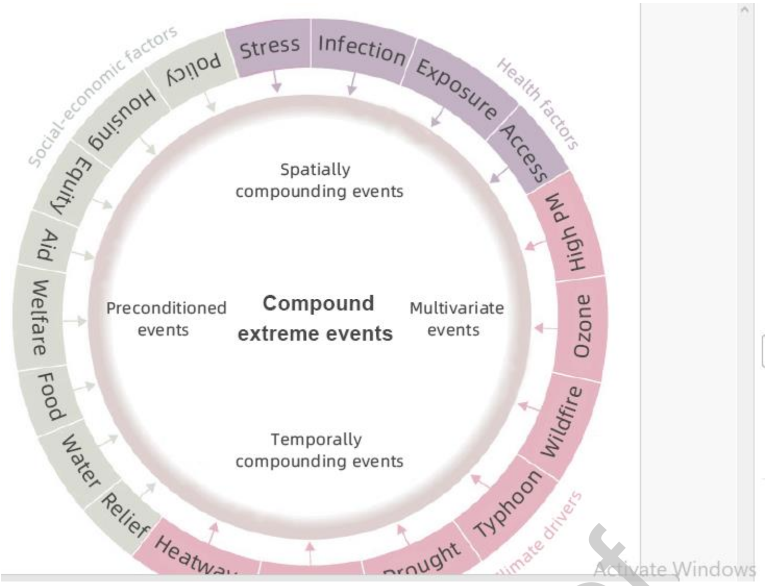

Fig. 1. Schematic diagram of compound extreme event classification and the key climate, health, and socioeconomic factors that drive their occurrence and impact. The inner circle shows the four types of compound extremes. Surrounding this, the outer ring lists core climate drivers, health factors, and socioeconomic factors. Arrows connecting the outer ring to the inner circle indicate the pathways through which each driver/factor influences the development and societal impacts of compound extreme events. Specifically, climate drivers trigger hazard occurrence, health factors shape population vulnerability, and socioeconomic factors determine risk patterns and adaptive capacity.

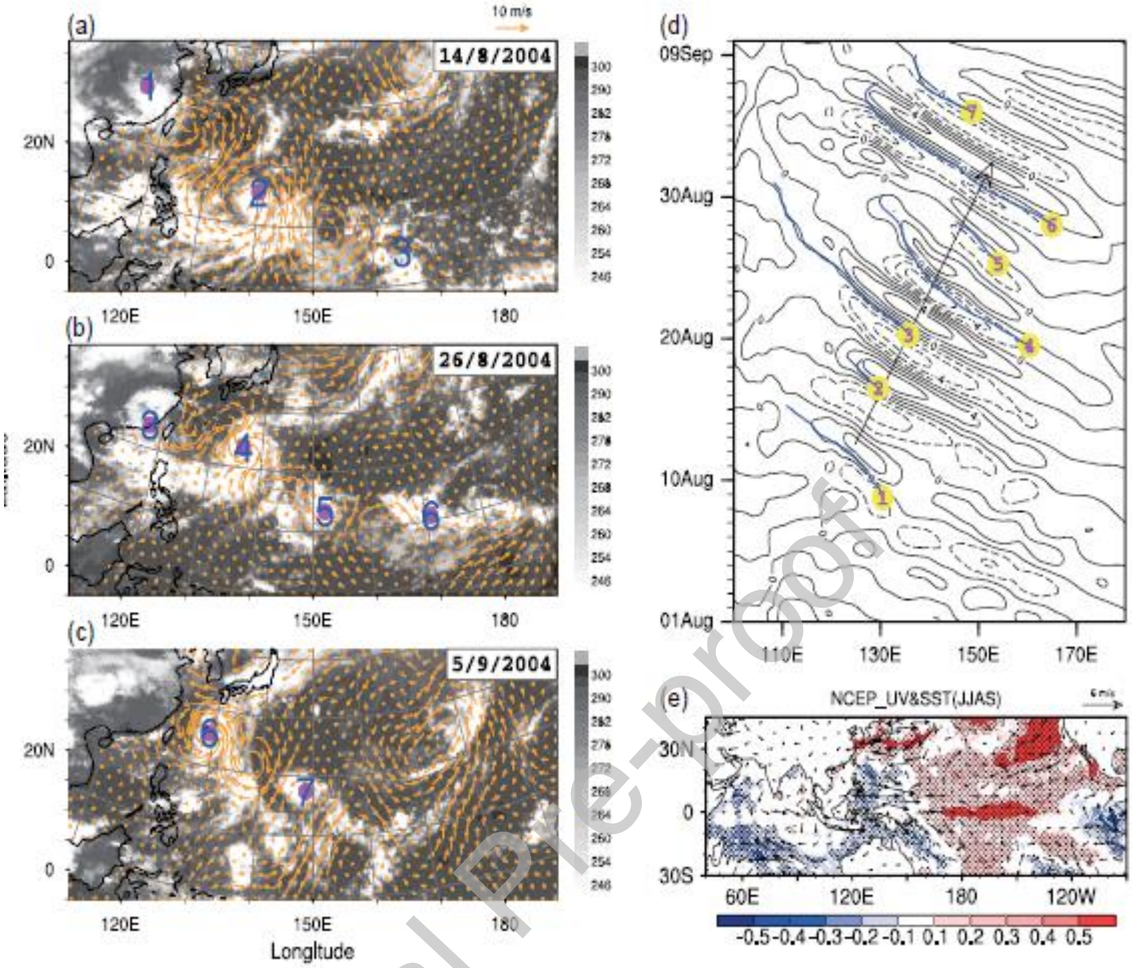

Fig. 2. The 3- to 8-day filtered 10-m winds (vectors) and brightness temperatures (gray shading; unit: K) on (a) 14 August, (b) 26 August, and (c) 5 September 2004. (d) Hovmöller diagram of the 3- to 8-day filtered 10-m meridional winds averaged over 5°–25°N for the period of 1 August to 10 September 2004. (e) Anomalies of summer mean sea surface temperature (color shading; unit: K) and 850-hPa winds (arrows; unit: m s^{-1}) in 2004. Adapted from Hu et al. (2018).

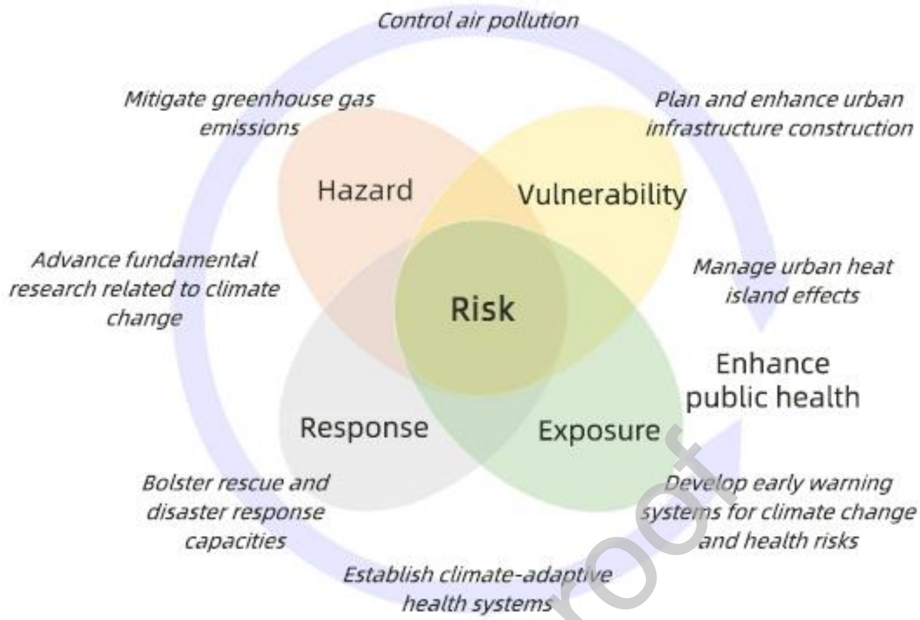

Fig. 3. Conceptual diagram of a compound extreme event response plan framed by the IPCC climate risk definition (risk arising from the interaction of hazard, vulnerability, and exposure, mediated by response). The four overlapping ovals represent the core risk components, whose intersection defines the overall risk. Encircling these are integrated strategies, all aimed at safeguarding and enhancing public health under compound extremes.