Understanding heatwave-drought compound hazards and impacts on socio-ecosystems

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As the Earth warms, the frequency and severity of weather and climate-related extremes are steadily increasing in most regions worldwide. A critical concern is the simultaneous occurrence of climatic extremes in the same location, referred to as compound events. Among these, Heatwave-Drought Compound Events (HDCEs) are one of the most destructive hazards, exacerbating impacts on human societies and ecosystems more than individual extremes. Therefore, it is necessary to understand the physical mechanisms behind HDCEs and to project their future changes and implications for socio-ecosystems. In this Perspective, we explain the motivation for understanding HDCE dynamics, describe new protocols to explore the water-heat-carbon coupling processes driving HDCEs, and finally outline future changes in HDCEs as well as their impacts on economic development and the carbon cycle.

THE EXTREME HEATWAVE-DROUGHT COMPOUND EVENT IN 2022

In recent decades, HDCEs have affected most regions of the globe, including Europe and western Russia in 2003, 2010, 2015, and 2018; the USA in 2011−2013; Australia in 2013; and southwestern and northern China in 2006, 2014, and 2022.[1] In 2022, an unprecedented hot summer scorched many regions of the world and received global attention. This extraordinarily warm event spread over the Northern Hemisphere, with China and Europe especially suffering from long-lasting extreme heat. The United Kingdom shattered records as temperatures soared above 40 ºC for the first time since meteorological measurements began.[2] China also faced multiple widespread heatwaves which hit over 400 cities and resulted in financial losses from crop failure of over $7.6 billion.[3] As heatwaves and droughts can be initiated by similar synoptic circulation anomalies (i.e., water deficit and energy demand), droughts are a common accompaniment to heatwaves. Due to these mechanisms, HDCEs are increasingly affecting our society and ecosystems in a warming planet. For example, the drought that accompanied the 2022 hot weather in Sichuan Province, in the upstream of the Yangtze River (a region with abundant hydropower), led to electricity shortages and posed critical pressure on people's work and lives. The adverse impacts of the power shortages in Sichuan were felt in locations as distant as Shanghai, a cosmopolis which relies heavily on electricity supply from other provinces. In addition, the widespread event in 2022 also negatively affected the biosphere's carbon assimilation capacity due to mortality of plants and increasing occurrences of wildfires. After severe climate hazards, plant recovery usually lags due to slower growth rate, irreversible damages in hydraulic conductance and carbon storage depletion. This delayed recovery can in turn elevate the vulnerability to a successive climatic hazard, which can hamper terrestrial carbon assimilation.[4]

HDCEs are now regarded as one of the most damaging climate-related stressors for global sustainable development, threatening the livelihood and welfare of human beings. Understanding their dynamics in our warming planet is thus important for achieving the Sustainable Development Goals (SDGs) set by the United Nations, particularly SDG13, which highlights the importance of mitigating climate change and associated impacts. Addressing this issue is also essential for implementing China's carbon neutrality strategy and achieving the sustainability development pathways.[5] However, the physical mechanisms behind concurrent heatwave-drought hazards remain poorly understood, especially from the perspective of land-atmospheric interactions under an intensified water cycle. Furthermore, the question of how terrestrial water storage (TWS, an essential determinant of the global water-energy budget) may drive the occurrence of concurrent hazards as well as their socio-ecosystem effects remains unexplored.

PHYSICAL MECHANISMS BEHIND COMPOUND EVENTS: THE ROLE OF WATER-HEAT-CARBON COUPLING

In 2022 and 2023, our team of hydrologists, economists, ecologists, and atmospheric scientists from China, the United States, United Kingdom, and Japan collaborated to address the above issues, and the research outcomes were published in Nature Sustainability.[6] This work systematically disentangles the physical mechanisms of concurrent hazards as well as their socioeconomic and ecological impacts under climate change. We employed a combination of field observations, Gravity Recovery and Climate Experiment (GRACE) satellite, machine learning-constrained reconstructions and the ERA5 reanalysis, and found a negative coupling between the land-water-content indicators (e.g., TWS) and temperature. This significant negative relationship ($p < 0.001$) implies that water-related hazards (e.g., droughts) and heat extremes are deeply interlinked and therefore should not be assessed in isolation, but instead should employ a more sophisticated framework.

Understanding the influence of atmospheric dynamics (i.e., water and energy transport) on climate extremes is essential to explain the mechanisms generating concurrent hazards. To achieve this goal, we estimated the anomalies of various water and heat variables during different climate-related extremes. In the extratropic, heat extremes occur with strong convective available potential energy and convective inhibition (Figure 1A). This synthetic energy-inhibition system is also associated with higher sensible heat, latent heat, and atmospheric total water vapor, accompanied by higher specific humidity in the Northern Hemisphere. Nevertheless, low-level moisture transport weakens during heat events, as denoted by widespread negative anomalies of moisture convergence, and results in decreasing relative humidity over land (Figure 1B-C). In the tropics and in many regions of the mid-latitudes, convective available potential energy is constrained, accompanied by strong convective inhibition, and limited water-heat transport strength. Extreme heat events favor atmospheric conditions with severe air dryness and lower precipitation, and therefore have high likelihood of translating into droughts and triggering a concurrent heat-drought event.

After elucidating the role of atmospheric dynamics in constraining the joint occurrence of heatwave-drought events, we sought to quantify the impacts of water and energy limitations on the terrestrial carbon budget. As carbon flux data is sparse at the global scale, we combined in situ eddy-covariance field measurements, a light use efficiency theory-based Gross Primary Productivity (GPP) product, and a machine-learning-based solar-induced chlorophyll fluorescence dataset. The energy demand for vegetation photosynthesis can be represented by temperature.[7] When the temperature is low, GPP increases with warming, as warming promotes photochemistry. When the environment is hot, further increases in temperature can cause GPP stress (Figure 1G), thus inhibiting plant photosynthesis and carbon uptake. Total ecosystem respiration (TER) grows with temperature, but at a more moderate rate than GPP (Figure 1H), therefore the net ecosystem carbon exchange still responds negatively to the highest temperature (Figure 1I). As water stress (via TWS depletion) can affect both GPP and TER, low TWS limits plant photosynthesis through stomatal and non-stomatal regulation as well as respiration through soil enzyme activities.[8] Under concurrent hot temperature and dry water storage, the average anomalies (-1.42 gC m^{-2} d^{-1})
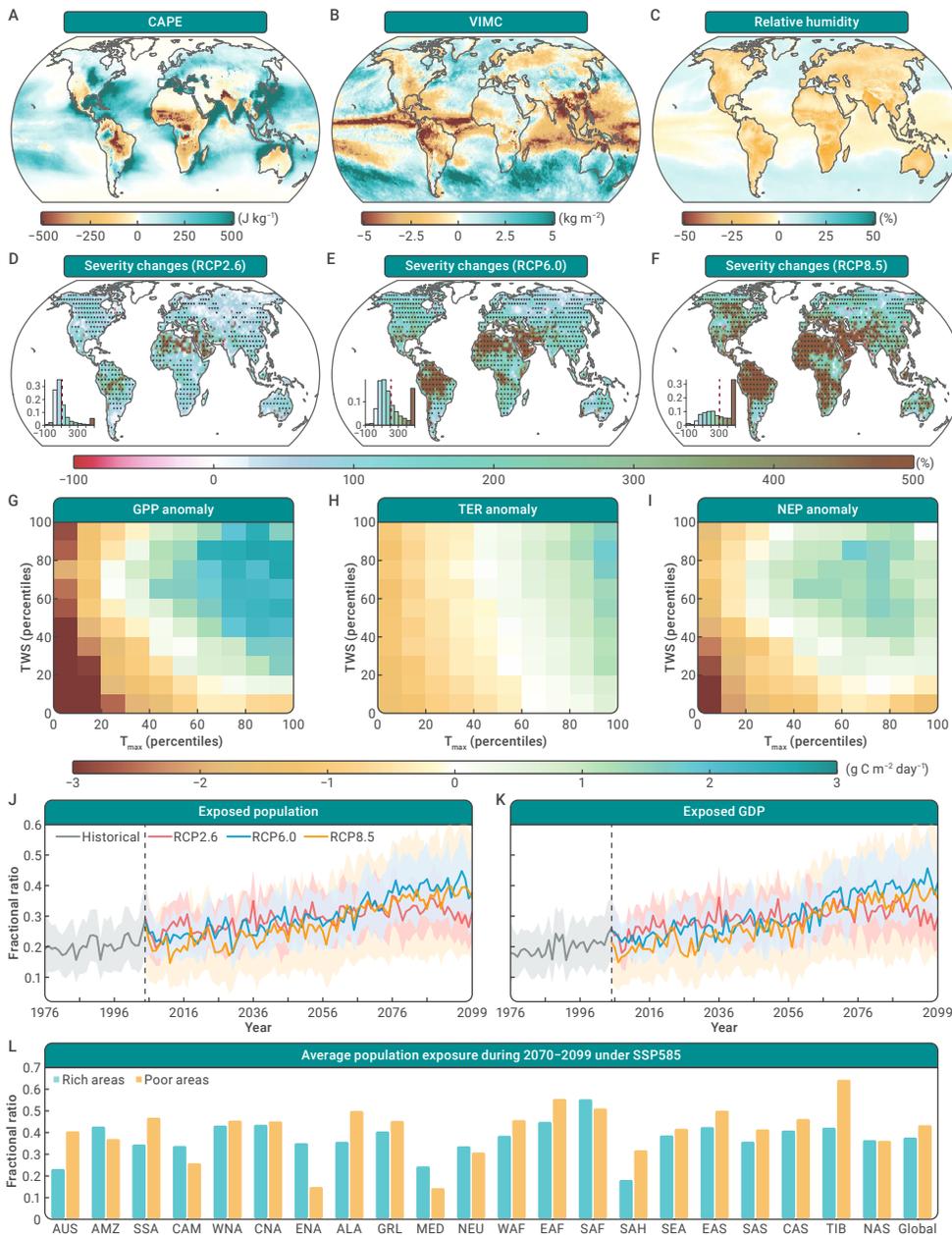
Figure 1. Changes in concurrent hazards and their socio-ecosystem effects A-C, Anomalies of convective available potential energy (CAPE) (A), atmospheric integrated moisture convergence (VIMC) (B) and relative humidity (C) during extreme heat events over the period 2002-2020. D-F, Relative changes in the severity of concurrent hazards from the historical (1976-2005) to future (2070-2099) periods; inset histogram indicates the relative change percentages, with the dashed vertical line denoting the average value; stippling denotes regions where the sign of the relative changes is consistent with the sign of the multi-model mean in at least 80% of models. G-I, Anomalies of GPP (G), TER (H), and NEP (I) above the 90th percentiles of temperature and below the 10th percentiles of daily TWS across 73 in situ eddy-covariance sites. J-K, Long-term changes in the global average exposed population (J) and exposed GDP (K) to concurrent hazards; the shading represents ±1 SD. L, Average population exposure fraction to concurrent hazards during 2070-2099 in rich versus poor areas under SSP585.

China, India, Russia, Southeast Asia, Amazon basin, Africa, Australia, and US (Figure 1D-F).

Water stress and energy demand both adversely affect carbon uptake; however, the question of whether the relationship might shift under an intensification of these concurrent hazards deserves a more detailed investigation. We showed that the negative effects of extreme dry TWS on GPP are projected to have a more adverse role than heat stress in future climates over 70-80% of global land areas, suggesting that water limitation may be increasingly important for future terrestrial carbon assimilation. To project future impacts of climatic extremes on ecosystem productivity, we also used the GPP, autotrophic respiration and heterotrophic respiration outputs from the CLM4.5 model under historical conditions and two RCPs (RCP2.6 and RCP6.0), forced by bias-corrected GFDL-ESM2M outputs. As expected, photosynthesis and respiration both decrease during concurrent hazards. This finding is supported by significant negative anomalies of carbon fluxes (i.e., GPP, TER and NEP) in most land areas worldwide, suggesting large decreases in terrestrial ecosystem carbon assimilation in a warming future.

of net ecosystem productivity (NEP) are substantially determined by GPP anomalies (-1.25 gC m^{-2} d^{-1}), which are both negative. This finding thus underscores the critical role of water stress and energy demand in limiting terrestrial carbon assimilation, and the adverse impacts of concurrent hazards on ecosystem health.

PROJECTION OF FUTURE CLIMATIC EXTREMES AND THEIR IMPLICATIONS FOR CARBON UPTAKE

To project future climatic extremes and their impacts on carbon assimilation, we employed 111 climate-hydrology model members, including 96 model-scenario combinations (i.e., three emission pathways, eight terrestrial hydrological models, and four Earth system models) under the Inter-Sectoral Impact Model Intercomparison Project phase 2b (ISIMIP2b) and 15 members (i.e., three SSPs and five Earth system models). We drove a global hydrological model (i.e., H08) with bias-corrected outputs from the latest Coupled Model Intercomparison Project Phase 6 (CMIP6). The global climate models, dynamic global vegetation model and global hydrological model were combined into as a model cascade chain to obtain future projections of concurrent heatwave-drought hazards. By the late 21st century, the occurrence and severity of these concurrent hazards are both projected to increase four-fold in most regions, with a significant intensification over southern

ECONOMIC INEQUALITY DUE TO HEATWAVE-DROUGHT COMPOUND EVENTS

An important consideration is how worsening climatic extremes might affect society through the exposure of population and regional Gross Domestic Product (GDP). To quantify these impacts, we employed the shared socioeconomic datasets covering the period 2010−2100. We defined exposure as the percentage of GDP (or population) affected by HDCEs to the total GDP (or population).[9] Under all emission pathways, our cascade modeling chain projects that the fraction of population and GDP exposed to concurrent hazards would substantially increase throughout the 21st century. Under the medium and high carbon emission scenarios, global population exposure and GDP exposure are projected to increase from ~16% during the reference period to ~40% by the late of 21st century (Figure 1J-K). An additional ~1.4 billion to ~1.7 billion people (~13 trillion to ~20 trillion U.S. dollars at 2015 PPP) per year are projected to be exposed to this concurrent hazard in the future period. These results show that climatic hazards are likely to threaten society and ecosystem productivity increasingly in a warmer future.

As poor populations often live in higher-risk regions with limited adaptability to stress from extreme heat and drought, they are likely to be more

exposed and vulnerable to climate-related hazards than wealthier populations.[10] We find that poorer populations (i.e., in grid cells of the globe where the GDP per capita falls below the 20th percentile in each climate region) are likely to experience more severe compounding hazards in most regions than wealthy populations. For example, poorer regions tend to have population and GDP exposure rates to HDCEs that are 10-20% higher than richer regions (i.e., grid cells where the GDP per capita is above the 80th percentile in each climate region) (Figure 1L). People living in urban areas tend to have greater ability to adapt, mitigate, and insulate their livelihoods from the adverse effects of these climate-related hazards. We find that rural regions are projected to experience more severe socioeconomic exposure than urban regions under climate change across all emission pathways. The above findings raise notable concerns regarding future climate-driven socioeconomic inequalities for people with lower levels of income. These effects are likely to further widen the economic gap between poorer and richer populations.

CONCLUDING REMARKS

We demonstrate that compound hazards are projected to increase substantially in the future, with disproportionate impacts on global ecological and socioeconomic productivity and more adverse effects in poor or rural areas. Our cascade modeling chain may have uncertainties in projecting future climate extremes arising from model structure, parameters, and interaction effects. However, our study firmly suggests that, in order to achieve ecosystem sustainability and mitigate the adverse impacts of warming on the environment, mitigation and adaptation strategies are urgently needed. The world should focus greater attention on socioeconomic inequalities, especially in high-risk regions that are expected to face more severe climatic hazards. Moreover, we hope our findings will encourage future efforts to explore the complicated water-carbon-economy nexus to seek practical solutions for achieving carbon neutrality in China and around the globe.

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ACKNOWLEDGMENTS

DECLARATION OF INTERESTS

The authors declare no competing interests.