Disasters collide at the intersection of extreme weather and infectious diseases

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Abstract

It is well understood that natural disasters interact to affect the resilience and prosperity of communities and disproportionately affect low income families and communities of color. However, given the lack of a common theoretical framework, it is rare for these interactions to be well understood or quantified. As an example, we consider the interaction of severe weather events (e.g., hurricanes and tornadoes) and epidemics (e.g., COVID-19). Observing events unfolding in southeastern U.S. communities has caused us to conjecture that the interactive effects of catastrophic disturbances and stressors might be much more considerable than previously recognized. For instance, hurricane evacuations increase human aggregation, a key factor that affects the transmission of acute respiratory infections like SARS-CoV-2. Similarly, weather damage to health infrastructure could significantly reduce a community's ability to provide services to people sick with COVID-19 and other diseases. As globalization and human population and movement continue to increase and weather events due to climate change are becoming more intense and severe, such complex interactions are expected to magnify and significantly impact environmental and human health.

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Abstract

Natural disasters interact to affect the resilience and prosperity of communities and disproportionately affect low income families and communities of color. However, due to lack of a common theoretical framework, these are rarely quantified. Observing severe weather events (e.g., hurricanes and tornadoes) and epidemics (e.g., COVID-19) unfolding in southeastern U.S. communities led us to conjecture that interactions among catastrophic disturbances might be much more considerable than previously recognized. For instance, hurricane evacuations increase human aggregation, a factor that affects the transmission of acute infections like SARS-CoV-2. Similarly, weather damage to health infrastructure can reduce a community's ability to provide services to people who are ill. As globalization and human population and movement continue to increase and weather events are becoming more intense, such complex interactions are expected to magnify and significantly impact environmental and human health.
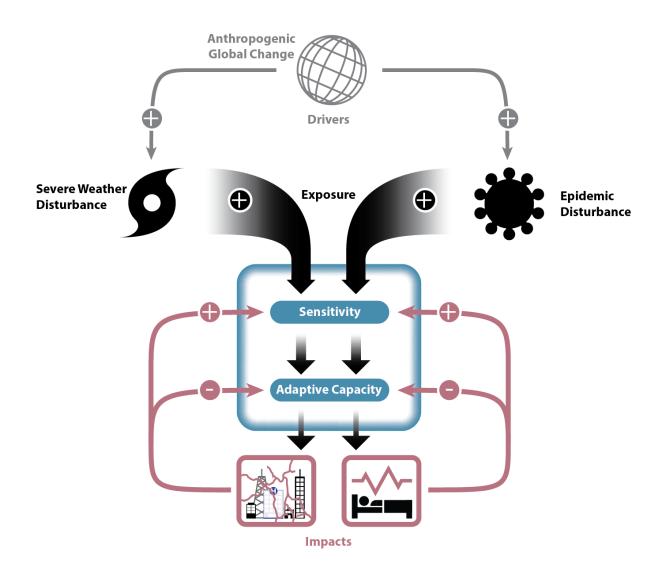
Introduction

Five of the top thirteen global risks are environmental in nature, more than any of the other threat categories, which concern economic, geopolitical, societal, and technological risks, respectively (World Economic Forum 2022). Anthropogenic global changes, including both climate change and social change along with high human population in disturbance-prone areas, are resulting in changes in the intensity of catastrophic weather events like flash floods and hurricanes, wildfire, epidemics of emerging infectious diseases like COVID-19, and other humanitarian disasters (Stephens *et al.* 2014; Kossin *et al.* 2020).

Such events represent disturbances to the agricultural, economic, environmental, and social systems that provide for human welfare and stability. Systems for forecasting, mitigating, and adapting to the damages of such events exist for these disturbances, but we lack a unifying scientific framework for considering the impacts of *massive compounded disturbances*.

The idea of compounded disturbances was introduced by Paine *et al.* (1998) to refer to the effect of increasing perturbations on the usual "cycles of disruption and recovery" in ecosystems. We use the modifier "massive" to specify disruptions at the scale of "billion dollar events" as tracked by the US National Oceanic and Atmospheric Administration (Smith 2020), though we extend the concept to all environmentally induced social disturbances. The science of massive compounded disturbances is an important subject for study because these disturbances are likely to interact. For instance, catastrophic wind disturbances may exacerbate the transmission of infectious diseases by damaging infrastructure and inhibiting access to medical care or by modifying mobility and contact patterns as people relocate to emergency shelters or refugee communities.
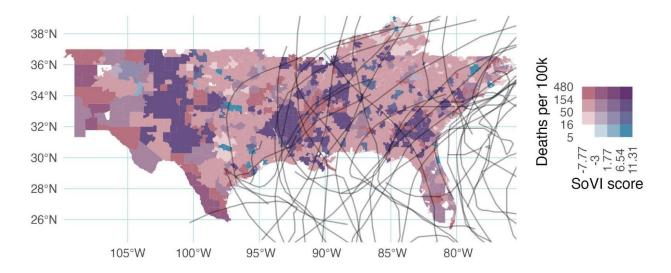
Conceptual Challenges

The *threat landscape* for such compounded disturbances is heterogeneous. Disturbances always affect specific people in specific places. Around the world and within nation states, populations are subject to wide variation in vulnerability. Social vulnerability to environmental disturbance consists of the three components of exposure, sensitivity, and adaptive capacity (Thomas *et al.* 2019). Exposure refers to variation in the frequency and magnitude of disturbances experienced by different communities (Shepherd & Binita 2015). Sensitivity refers to characteristics or conditions that make people more likely to be affected by exposures (Yu *et al.* 2021). Adaptive capacity refers to the ability of systems, institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to

consequences (Allen & Holling 2010; Intergovernmental Panel on Climate Change 2015). Understanding the interacting effects of compounded disasters and the distribution of threats within the global population is an important scientific challenge that must be addressed to achieve progress in environmental justice (Figure 1). We suggest that the science of colliding disasters is ripe for conceptual development and empirical analysis. However, we largely lack the theory needed to frame the science of colliding disasters, which we submit is a grand challenge for the integration of social and natural science approaches to understanding anthropogenically driven global change.

Figure 1. Massive compound disturbances and community vulnerability. Anthropogenic changes can drive increases in the frequency and intensity of multiple types of environmental disturbances, increasing a community's exposure to risk. Impacts on a community are a function of the level of exposure, the community's sensitivity to various forms of disturbance, and the mitigating effect of the community's adaptive capacity, or resilience. Negative impacts from one type of disturbance can increase the community's sensitivity to other types of disturbance, and reduce the community's capacity to adapt to multiple types of disturbance. These feedbacks can happen synchronously or asynchronously, especially in the case of disturbances with long lasting impacts, such as hurricanes and epidemics.

For example, we conjecture that extreme weather events and epidemics interact over multiple time frames and spatial scales. At the smallest time and spatial scales, we hypothesize that evacuees seeking emergency shelter are brought into direct contact with one another in ways that accelerate transmission (Pei *et al.* 2020). But, the most significant effects of extreme weather are not so immediate. We know that the long shadow of extreme weather events may affect communities for years to decades. The southeastern United States, where we live, is subject to frequent hurricanes and tornadic activity (Gensini & Brooks 2018) and was also subject to devastating impacts of the COVID-19 pandemic. Just as it was recently shown that cancer care in the southeastern U.S. was negatively affected by Atlantic hurricanes (Espinel *et al.* 2022), we hypothesize that hurricanes that occurred long before the beginning of COVID-19 damaged communities in measurable and unmeasurable ways such that when hit by a secondary disturbance (COVID-19), negative health outcomes (e.g., case fatality rate) were exacerbated in communities that had already suffered social and environmental damages from hurricanes (Figure 2).

Figure 2. Intersection of social vulnerability, hurricanes, and COVID-19 outcomes for HHS regions 4 and 6. Map regions (Hospital Service Areas) are colored by Social Vulnerability Index for the United States (SoVI®; Cutter *et al.* (2003)) 2010–2014, a measure of sensitivity, and cumulative deaths per 100,000 from COVID-19 through 2020 (Dong *et al.* 2020). High SoVI® scores indicate high relative social vulnerability. SoVI® scores are aggregated to HSA from county-level scores by population. Tracks of all hurricanes intersecting the study area from 2015 through 2020 are shown in gray (Landsea & Franklin 2013). Spatial autocorrelation and the need to integrate different kinds of data (i.e., the irregular tiling of HHS regions and hurricane tracks) make developing suitable methods for hypothesis testing an important problem for further research.

These hypotheses point to a number of conceptual gaps. Over what time scales are the negative environmental impacts of extreme weather events felt by different communities? How do the elements of social vulnerability (exposure, sensitivity, and

adaptive capacity) affect the magnitude and durability of these negative environmental impacts? At what lags should we expect the impacts of massive compounded disturbances to be felt? Where do the causal arrows lie? Would a community's experience of COVID-19 also affect its future vulnerability to extreme weather? We think so. Even though COVID-19 does not conceivably affect the physical properties of the weather (e.g., wind speed and rainfall), the effects of extreme weather are unavoidably mediated by community resilience, which certainly has been affected by differential impacts of COVID-19. These are key questions for conceptual analysis and theorization.

Data Challenges

The science of colliding disasters will also face a number of informational challenges. Here we distinguish between challenges of scope, variation, relevance, and resolution.

Scope. The science of colliding disasters concerns the distribution of hazards among multiple populations, i.e., large spatial extents. To quantify compounding disturbances will require collecting commensurate data across multiple populations.

Variation. Understanding interactions between hurricanes and epidemics will require a nuanced understanding of several sources of variations. The endogenous factors of a hurricane include timing, intensity (quantified as wind speed and level of flooding), and proximity to the higher and moderate intensity disturbance. Moreover, sequences of storms may overlap in their effects. For diseases, a wide variety of demographic, socio-economic, and political factors affect health outcomes, including race, ethnicity, and socioeconomic deprivation (Green *et al.* 2021; Upshaw *et al.* 2021).

Relevance. The science of colliding disasters is primarily about the causes and distribution of impacts, i.e., hurricane damages, flooding, negative health outcomes, etc. These are different to the data that are most often used when quantifying disasters, i.e., wind speed, rainfall, and number of cases. Similarly, measures of social vulnerability vary in their relevance to vulnerability to environmental disturbances. For our area, the Baseline Resilience Indicators for Communities (BRIC) index developed by the Hazards Vulnerability & Resilience Institute (Cutter *et al.* 2014) is probably the most relevant, but this index has not been updated since 2015.

Resolution and integration of data types. To usefully measure variation in massive compounded disturbances, data must be resolved to the level of communities to be compared. In the U.S., a lot of data are available at the level of counties. But counties contain disparate communities and may exhibit considerable within-unit variation in race, wealth, education and other important sociodemographic properties (Rickless *et*

al. 2020). For instance, health outcomes of COVID-19 (e.g., death) are widely reported at the county scale, but deaths are reported by the county in which the death occurred, which is not necessarily the county in which the individual was exposed to natural hazards. Socioeconomic factors such as wealth and education are probably not randomly associated with the location in which one receives treatment. Hence, county level analysis distorts (and perhaps hides) the impact of socioeconomic disparities on health outcomes. A more appropriate approach is to conduct analysis at the level of Hospital Service Areas (HSAs) or Hospital Referral Areas (HRAs) (Nanda *et al.* 2021). This is possible only if raw data are collected at a much smaller spatial scale than counties, or through statistical interpolation.

A path forward

Here we sketch the steps that will be essential to develop a useful science of colliding disasters. We believe these steps could be taken in parallel and are not onerous (they take advantage of existing scientific institutions, structures, and data), but do require deliberate coordination because of the inherently multi-disciplinary challenge of understanding massive compounded disturbances.

Conceptual framing. The science of colliding disasters will require contributions from natural sciences, economics, social science, engineering, and health science paradigms. To avoid duplicating effort and wasting time and expertise, it is essential that a suitable transdisciplinary working group be formed to tackle the challenges of integrating disparate technical vocabulary, conceptual frames, and methodology. A set of core concepts and unifying principles should be defined and used consistently to ensure that research objectives are well-posed, relevant, and feasible.

Data compilation. Key data should be identified and compiled to suitable resolution. One of the challenges of multi-disciplinary research is distilling the data to such a degree that the key concepts are properly represented. Each individual discipline has, of course, a plethora of canonical data streams that are acquired to meet the needs of the intra-disciplinary research questions. Such granularity may not be needed (and may actually impede progress) to address the inter-disciplinary questions presented by the science of compounded disturbances.

Analysis. Finally, analytical workflows must be designed to address the new questions of the colliding disasters paradigm. The central role of social vulnerability and spatial extension of disturbance events suggests that models of compounded disturbances will be inherently spatial. Hence, the spatial autocorrelations intrinsic to such data interfere with the proper interpretation of findings unless suitable models can be contrived. This

problem is compounded by the fact that the different kinds of processes envisioned (social processes, atmospheric processes, etc.) occur at different spatial scales and may be recorded in incommensurable data types, e.g., the spatial tiling of COVID-19 health outcomes among HSAs and the line segments that represent hurricane tracks (Gotway & Young 2002).

In conclusion, we believe that there is currently a need for a new science of colliding disasters. The challenges inherent in such an enterprise are neither trivial nor insurmountable. They should be met by a deliberate transdisciplinary effort. This will ensure that as rapid changes are occuring around the planet, we are able to provide predictive values to such interactions to enhance the resilience and recovery of coupled natural and human systems.

Acknowledgements

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