

From local hazards to connected climate risk: Compound extremes reveal a systemic blind spot

Luis Gimeno-Sotelo,^{1,2} Patricia Coll-Hidalgo,³ Raquel Nieto,⁴ and Luis Gimeno^{4,*}

¹Departamento de Ciências Matemáticas, Faculdade de Ciências, Universidade de Lisboa, Lisboa 1749-016, Portugal

²CEAUL – Centro de Estatística e Aplicações, Faculdade de Ciências, Universidade de Lisboa, Lisboa 1749-016, Portugal

³Instituto Português do Mar e da Atmosfera (IPMA), Lisboa PT 1749-077, Portugal

⁴Centro de Investigación Mariña, Universidade de Vigo, Environmental Physics Laboratory (EPhysLab), Ourense 32004, Spain

*Correspondence: l.gimeno@uvigo.es

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Climate risk is commonly assessed through local indicators that diagnose hazards where impacts occur. These indicators remain indispensable for operational monitoring, impact assessment and adaptation planning. However, many compound extremes develop through interacting atmospheric, hydrological and land-surface processes extending beyond the affected region. Large-scale circulation, atmospheric moisture transport, heat redistribution and land-atmosphere coupling can connect distant regions, favour compound hazards and influence how their impacts propagate across sectors. Here we argue that climate-risk assessment can be strengthened by complementing local indicators with diagnostics of these connected Earth-system processes. The novelty is not the recognition that climate processes are connected, but an explicit process-based framework in which upstream climate anomalies influence local hazards through identifiable circulation, moisture- and heat-transport, and land-atmosphere pathways, after which their impacts may cascade through interconnected socioeconomic systems. This approach has implications for prediction, attribution and adaptation while preserving the central role of local information.

LOOKING BEYOND LOCAL HAZARDS

Climate-risk assessment has traditionally been organized around the locations where hazards and impacts become observable. Droughts are identified through precipitation deficits, heatwaves through local temperature anomalies, floods through runoff or river-discharge thresholds, and wildfire danger through regional fire-weather conditions. These approaches have transformed operational monitoring, disaster response and adaptation planning, and they remain essential for diagnosing hazards and assessing their local consequences. However, their necessary focus on local conditions means that they do not always capture the larger-scale physical processes contributing to hazard development.

For many compound climate extremes, this local perspective provides only part of the physical explanation. Their development frequently involves interacting atmospheric, hydrological and land-surface processes operating across multiple spatial scales and connecting distant regions of the Earth system. Large-scale circulation anomalies, atmospheric moisture transport, heat redistribution and land-atmosphere coupling can favour simultaneous or sequential hazards across distant regions and shape the conditions under which their impacts subsequently cascade across sectors.

The physical conditions contributing to climate risk may therefore develop well beyond the region in which hazards eventually become observable. This distinction is particularly relevant for compound extremes, which are increasingly recognized as some of the most consequential risks in a warming world.¹ Drought-heatwave events, wildfire-heat interactions, concurrent agricultural failures and cascading flood events can affect food production, water resources, infrastructure, ecosystems, energy systems and public health simultaneously or in close succession. Local indicators remain essential for assessing these impacts, but their interpretation can be strengthened by explicitly considering the connected physical processes that contribute to compound hazard development.

The limited integration of these connected physical processes into existing risk frameworks represents an important blind spot in the assessment of compound climate risk.²

COMPOUND EXTREMES ARE CONNECTED PHENOMENA

Compound extremes combine multiple climatic drivers or hazards occurring simultaneously, sequentially or across regions. Although useful for identifying compound conditions, the local framing may not fully reveal the physical processes connecting their development.³ For example, drought-heatwave events can develop through interacting moisture and heat pathways

involving atmospheric circulation, moisture transport, soil-moisture depletion and sensible heating. Remote atmospheric moisture deficits can contribute to reduced precipitation and soil-moisture availability,⁴ while persistent circulation anomalies and reduced evaporative cooling favour heat accumulation. These processes may reinforce one another across connected regions, increasing the persistence or severity of the resulting hazard beyond that expected from local conditions alone.

Representative examples show Earth-system connectivity across diverse compound extremes. Atmospheric rivers transport moisture from distant oceanic sources towards areas where they can contribute to extreme precipitation, flooding and landslides.⁵ Upwind drought and soil-moisture depletion can intensify downstream heat through reduced evaporative cooling and enhanced sensible heat transport.⁶ Persistent Rossby wave trains and blocking can favour droughts, heatwaves and wildfire-conducive conditions across distant regions. Land-atmosphere coupling can reinforce these connections through evapotranspiration, moisture recycling, surface-energy partitioning and boundary-layer dynamics. Mediterranean droughts offer another example: reduced moisture uptake or transport from remote sources can contribute to regional precipitation deficits.⁴

What appears locally as an isolated hazard may therefore represent the regional expression of physical processes evolving across a dynamically connected Earth system. Compound extremes may therefore involve more than the statistical coincidence of multiple hazards: in many cases, their development reflects interacting physical processes operating across regions and scales.

THE LIMITS OF AN EXCLUSIVELY LOCAL PERSPECTIVE

Despite major advances in compound-event science, climate-risk assessment necessarily remains centred on regional indicators, sector-specific metrics and administrative decision-making scales. This organization is essential for monitoring impacts and supporting decisions, but it does not always represent the propagation and interconnectedness of the physical processes contributing to compound hazard development. Consequently, hazards may be monitored primarily at the regional scale even when some of their contributing physical drivers operate across much larger spatial domains.

An exclusively local perspective may have three related consequences. It can limit mechanistic interpretation when hazards are influenced by upstream circulation, remote moisture transport or large-scale land-atmosphere coupling; constrain anticipatory action by overlooking persistent blocking, moisture-source deficits, evolving transport pathways and antecedent soil moisture; and underestimate how local impacts propagate through interconnected socioeconomic systems. For example, drought-related agricultural losses can affect food supply chains and water availability, simultaneous heatwaves can amplify food and energy stress, and wildfire smoke or infrastructure disruption can spread beyond the original hazard region.

Together, these limitations indicate that local climate-risk assessment can benefit from a complementary perspective that explicitly represents both connected Earth-system processes and the subsequent propagation of impacts through socioeconomic systems.

Figure 1 summarizes this complementary framework. Panel A represents traditional climate-risk assessment based on local indicators; Panel B illustrates the connected Earth-system processes that contribute to hazard development before hazards become locally observable; and Panel C shows how locally manifested impacts subsequently cascade through interconnected socioeconomic systems. The figure also highlights potential applications for prediction, attribution and adaptation.

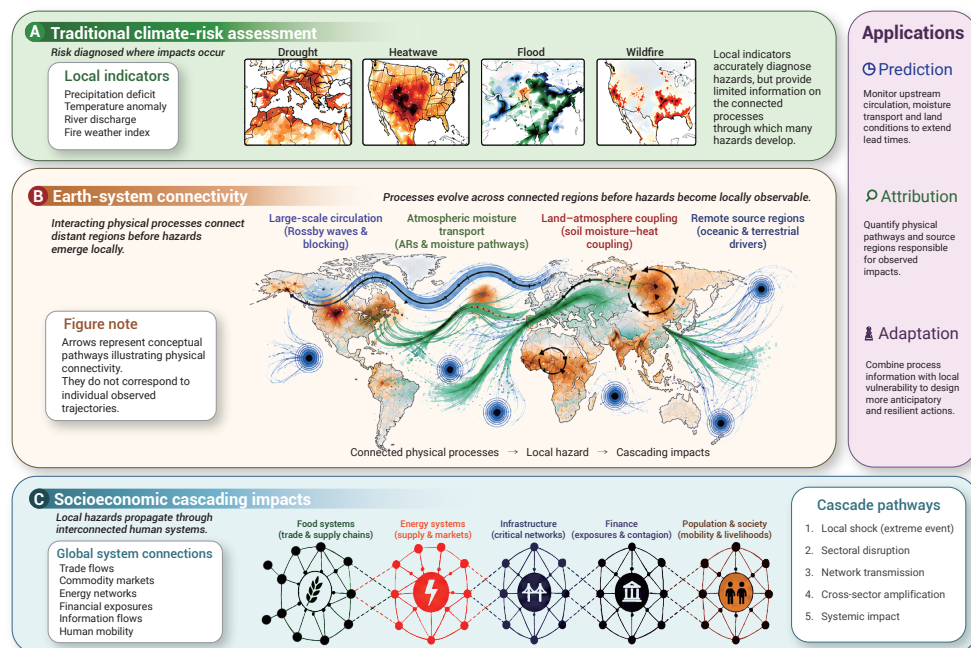


Figure 1. From locally diagnosed hazards to connected climate risk (A) Traditional climate-risk assessment diagnoses hazards where impacts occur using local indicators and thresholds. These indicators provide robust local hazard diagnosis but limited information on the connected physical processes through which many compound hazards develop. (B) Earth-system connectivity contributes to hazard development through large-scale circulation, atmospheric moisture transport, land-atmosphere coupling and remote source-region variability. All graphical elements were newly created for this manuscript as a conceptual synthesis informed by established process. The coloured arrows summarize conceptual physical pathways and should not be interpreted as individual observed trajectories. (C) Once hazards become locally manifest, their impacts may propagate through interconnected socioeconomic systems. The Applications panel illustrates potential uses for prediction, attribution and adaptation.

ingly important as climate change alters the intensity, persistence and spatial co-occurrence of compound extremes. The challenge is to retain the strengths of local assessment while improving understanding of connected physical processes and the socioeconomic

TOWARD CONNECTIVITY-BASED CLIMATE RISK SCIENCE

Addressing this blind spot does not require replacing local indicators, which remain indispensable for diagnosing hazards, monitoring impacts, assessing exposure and vulnerability, and supporting operational responses. They can be complemented by diagnostics of the connected physical processes through which compound hazards develop and by assessments of how their impacts propagate across socioeconomic systems. Connectivity-based climate-risk science links upstream drivers, local hazard development and cascading impacts. The underlying mechanism follows a process chain in which upstream climate anomalies modify circulation, moisture or heat transport, or land-atmosphere coupling; these physical pathways influence local hazard development, whose impacts may subsequently propagate across interconnected socioeconomic systems. Operationally, it comprises four components: identifying upstream drivers such as persistent circulation anomalies, moisture-source deficits, sea-surface temperature anomalies and antecedent land conditions; characterizing connecting pathways using moisture- and heat-transport diagnostics, circulation-persistence metrics, Lagrangian tracking and land-atmosphere coupling indicators; relating these diagnostics to locally observed hazards; and assessing impacts across interconnected food, water, energy, infrastructure, ecological and socioeconomic systems.

Implementing this workflow requires progress across three complementary dimensions. Observational and reanalysis data are needed to monitor upstream circulation, moisture transport and land-surface conditions. Earth-system models should be evaluated not only through local temperature and precipitation statistics, but also through their capacity to reproduce the physical pathways connecting remote drivers with regional hazards. These diagnostics should then be translated into applications for prediction, attribution and adaptation.

This framework has direct implications for prediction, attribution and adaptation. Early-warning systems could complement regional indicators by monitoring upstream circulation persistence, moisture-source deficits, transport pathways and antecedent soil moisture before hazards fully develop locally. Attribution can identify the pathways and source regions contributing to an observed hazard while distinguishing remote influences from local amplification. Adaptation can combine information on connected physical processes with local exposure and vulnerability. Separating Earth-system connectivity from socioeconomic cascading impacts can also support coordination across regions and sectors at different stages of risk development.

More broadly, it encourages compound extremes to be interpreted not only through their local expression, but also through the connected Earth-system processes that contribute to their development.

A NEW GEOGRAPHY OF CLIMATE RISK

The climate system does not operate according to administrative boundaries. Atmospheric circulation, moisture transport, heat redistribution and land-atmosphere coupling connect distant regions through pathways that influence compound hazards. Existing assessment captures their local manifestation effectively but less commonly incorporates the remote pathways contributing to their development. Representing these pathways is increas-

systems through which impacts propagate.

Local climate-risk assessment will remain indispensable because hazards, exposure, vulnerability and adaptive capacity are fundamentally location-specific. The opportunity is to complement this foundation with diagnostics of upstream physical drivers, Earth-system connectivity and cascading socioeconomic impacts. Compound extremes reveal why both perspectives are needed: one identifies where hazards and impacts become observable, while the other helps explain how they develop, propagate and interact across connected regions and sectors.

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AUTHOR CONTRIBUTIONS

All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.