

Understanding and Managing Connected Extreme Events

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Abstract

Extreme weather and climate events and their impacts can occur in complex combinations, an interaction shaped by physical drivers and societal forces. In these situations, governance, markets, and other decision-making structures — together with population exposure and vulnerability — create nonphysical interconnections among events by linking their impacts, to positive or negative effect. Various anthropogenic actions can also directly affect the severity of events, further complicating these feedback loops. Such relationships are rarely characterized or considered in physical-sciences-based research contexts. Here we present a multidisciplinary argument for the concept of connected extreme events, and we suggest vantage points and approaches for producing climate information useful in guiding decisions about them.

42 In 2017, a parade of severe tropical cyclones devastated the eastern Caribbean, with damages to
43 property and infrastructure that were exacerbated by the consecutive storms^{1,2} and by the
44 depleted response ability of the U.S. Federal Emergency Management Agency stemming from
45 Hurricane Harvey several weeks earlier³. A humanitarian crisis ensued, in which, predictably, the
46 populations with the highest baseline vulnerability tended to suffer most⁴. In 2018, an
47 exceptionally cold and wet early spring affected winter-cereal harvests and hindered spring
48 planting across Europe, and this compounded with a hot and dry summer to lead to agricultural
49 losses in consecutive cropping seasons — raising wheat and barley prices in the integrated
50 European Union market by 30% and straining the continent’s government and insurance
51 budgets^{5,6}.

52
53 We term such combinations of extreme events ‘connected’, to convey the diversity and
54 complexity of interacting physical and societal mechanisms that cause their impacts to be
55 amplified relative to the impacts from those same events occurring separately or univariately
56 (Table 1). Note that this definition includes hazards which result in impacts only or primarily via
57 feedback loops involving anthropogenic systems of some kind. Here we use ‘impacts’ to mean
58 the losses arising from the interaction of hazard, vulnerability and exposure (synonymous with
59 consequences or outcomes) and ‘risk’ to mean potential or unrealized losses, both as defined by
60 the IPCC⁷. Where such a distinction is not necessary, we use ‘impacts’ as a general term
61 encompassing both concepts.

62
63 As further elaborated in Box 1, ‘connection’ incorporates and builds upon the physical-hazard-
64 based framework of ‘compound’ weather and climate events⁸⁻¹²; ‘interacting’, ‘cascading’, or
65 ‘multi-risk’ natural hazards¹³⁻¹⁸, and systemic risks and complexity science¹⁹. Our discussion is
66 closely informed by advances and assessments in these fields, but hones in on attributes unique
67 to extreme weather and climate events and on the exacerbating role that anthropogenic actions
68 can play with regard to both their severity and impacts.

69
70 In this Perspective, we describe the broad applicability of the concept of connected extremes and
71 how relevant expertise, disciplinary knowledge, and insights inside and outside of academia can
72 best be solicited and employed so applied-science teams that include climate scientists focus on
73 the variables, metrics, locations, and temporal aspects of greatest societal importance. We reflect
74 on connected extremes through our research and practitioner experiences in the sectors of food,
75 water, human health, infrastructure, and insurance, and show how current risk-management
76 approaches fall short in addressing the complex challenges associated with connected extremes.
77 We then present specific recommendations for how collaborations among the research and
78 decision-making communities may be expanded and enhanced. Consequently, we also aim to
79 inform policies toward the adaptation and mitigation strategies most appropriate for reducing
80 risks from and increasing resilience to connected extremes, which may differ from those
81 designed for single extremes.

82

83 *Physical basis, societal relevance*

84 Connection between climate extremes can be conceived of as complex time- and space-varying
85 physical and societal mechanisms that relate one event to another (Figure 1), ultimately causing
86 major impacts (Figure 2) (see Box 1). In the case mentioned in the opening paragraph, a

87 connection was created between the impacts of Hurricanes Harvey and Maria, severe but
88 otherwise unrelated events that occurred 3300 km and 26 days apart³. Focusing on Hurricane
89 Maria's impacts in Puerto Rico — which included more than 3000 deaths and nearly \$100 billion
90 in damage — post-event reports identified the island's under-maintained infrastructure, limited
91 budget, aging population, and territory status as among the factors which contributed to its
92 vulnerability to Hurricane Maria^{3,4,20,21}. While the hazards of heavy precipitation and strong
93 winds caused large amounts of direct damage, such as road washouts and drownings, the impacts
94 were exacerbated by slow and patchy relief and recovery efforts. Emergency-response systems
95 had been stretched thin by Hurricane Harvey striking Texas the previous month and Hurricane
96 Irma striking Florida the previous week, with administrative mismanagement also coming into
97 play^{1,4,21-23}. As summarized by the U.S. Federal Emergency Management Agency [FEMA],
98 “FEMA not only exhausted commodities on hand but also exhausted pre-negotiated contracts to
99 provide meals, tarps, water, and other resources during the responses to Hurricanes Harvey and
100 Irma. Therefore, the concurrent response for Hurricane Maria required FEMA to rapidly solicit
101 vendors [...] Increased contract demands from the hurricane season severely taxed FEMA's
102 acquisitions process and contracting personnel...”³. Across Puerto Rico, mortality was highest in
103 isolated municipalities and those with low socioeconomic development, highlighting linkages
104 between vulnerability and impacts^{21,24}. The quality and equity of the rebuilt physical systems,
105 reimagined social-support networks, and revised decision-making structures will be reflected in
106 future exposure and vulnerability, and most tangibly in the impacts when combinations of
107 extreme events occur again^{23,25}.

108 We argue that these types of complexities mean that successfully parsing, preparing for, and
109 responding to connected extreme events requires deep collaboration across sectors and
110 disciplines. Physical hazards, for instance, are shaped by timing, location, and meteorological
111 context, while political, financial, infrastructural, and cultural networks make certain
112 combinations of events especially potent from an impacts standpoint, through their exposure and
113 vulnerability characteristics. These networks include traits strongly dependent on governance,
114 culture, historical precedent, information flow, and other legacies — ‘societal mechanisms’ that
115 are ever-changing and that can create systemic risks when interconnections result in fragility
116 rather than resilience^{19,26,27}, due to internal dynamics or external influences such as climate
117 change.

118 In this context of intrinsic interdisciplinarity, shifting relationships, and capacity for surprise
119 (such as the crossing of tipping points)²⁸, joint physical-societal assessments are critically
120 important for building scientific understanding and improving risk management in response to
121 connected extremes. Moreover, adaptation strategies are ever-evolving under a changing
122 climate²⁹, requiring iterative efforts to evaluate their efficacy³⁰. Not only must risks be identified,
123 monitored, and evaluated, but the risk-management process itself must be subject to reframing
124 and transformation to match the risks (or state of knowledge of them). Greater severity and
125 frequency of many hazards as a result of climate change, combined with a lower loss threshold in
126 populations with higher vulnerability, makes such efforts especially urgent.

127

128 *Societal impacts of connected extremes in five major sectors*

129

130 In this section, we provide examples of concepts and methods about connected extremes through
131 the lens of five sectors reflecting our research and practitioner expertise: food, water, human
132 health, infrastructure, and insurance. We discuss how each sector is affected; current responses
133 and their effectiveness; and important types of knowledge that new decision-relevant
134 collaborations could produce.

135

136 *Food*

137 The agricultural sector consists of a multitude of heterogeneous farming systems and complex
138 networks of food supply, demand, and trade that exhibit high systemic risk³¹. In this context,
139 connected extremes can threaten regional and global food security.

140

141 Crops are particularly vulnerable to multivariate hot and dry events that cause water stress, while
142 workers and livestock are burdened by hot and humid extremes that cause physiological
143 stress^{32,33}. The sequence in which extremes occur can exacerbate overall impacts, given crop
144 physiologies and the need for particular field conditions during key developmental stages³⁴.
145 Early-season floods can delay field preparation and planting, pushing back crop calendars in a
146 manner that exposes crops to late-season frost or drought stress. Early wet conditions may also
147 weaken plants' ability to cope with subsequent extremes by limiting their root depths or creating
148 conditions favorable for pest infestations. Alternatively, early-season drought can cause farmers
149 to deplete water resources and thus increase vulnerability to dry spells later in the season.

150

151 Currently, some crop models analyze water, nitrogen, and heat stress on each day and apply only
152 the largest stress factor, missing the compound nature of many hazards. Conditional effects are
153 also challenging for statistical crop-model yield projections, which for maximal accuracy would
154 require incorporation of the timing of extreme events as well as of cross-terms that identify
155 sequential connections between early- and late-season extremes of different variable types³⁵.

156

157 The confluence of all these issues is crystallized in considering the prospect of a multiple-
158 breadbasket failure, with extreme events striking two or more important agricultural production
159 zones, resulting in a large aggregate effect on global food production and prices^{36,37}. Such a
160 situation could result from independent regional extremes randomly co-occurring, or could have
161 a correlation structure driven by teleconnections linked to major modes of climate variability^{38,39}.
162 Recent decades have seen a consolidation of global production into fewer regions and a
163 proliferation of monoculture systems, increasing the potential for a small number of synchronous
164 regional-scale extremes to have widespread impacts⁴⁰. Agricultural trade models connect
165 regional production into wider balances of supply and demand to achieve long-term equilibria;
166 however, year-by-year actions of stakeholders along the value chains from field to global market
167 and from global market to supermarket shelf are not as well-simulated, hindering resilience
168 planning to 'shocks' such as those that connected extremes can induce.

169

170 To prevent food-system shocks, there is a great need for enhanced understanding of the impacts
171 of specific sequences of extreme events at a local scale, particularly if risks could be identified
172 early enough to allow for appropriate farming and trading countermeasures. Complementarily,
173 connection between extremes in the food context often manifests through non-farm elements
174 such as transport and processing, so incorporating this systems knowledge when designing

175 climate research — even if only as an initial consideration — would significantly improve its
176 usefulness.

177
178 Water

179 Access to clean water in sufficient quantities is a fundamental requirement for human societies.
180 In a growing and urbanizing world, water management and distribution are challenging but
181 unavoidable tasks, especially when both critical water states — flood and drought — can result
182 from a combination of physical drivers and be exacerbated by correlations among them^{41,42}.

183
184 Compounding effects can alter flood risk in several distinct ways. Antecedent conditions, such as
185 groundwater or soil moisture, often play a key role in flood generation¹⁰. Concurrent flood
186 drivers can be of the same type, such as discharge at river confluences⁴³, or different types, such
187 as the superposition of high tides, storm surges, waves, and freshwater inflow leading to extreme
188 total water levels along coastlines^{44,45}. Both spatial and temporal compounding play into the
189 severity and impacts of high- and low-water events and consequently the outcomes of
190 hydrological risk assessments^{46,47}. Analogously, droughts are inherently multivariate phenomena
191 that respond nonlinearly to changes in controlling parameters such as temperature, precipitation,
192 and soil moisture⁴⁸⁻⁵⁰. Furthermore, drought impacts are often largest when they compound
193 temporally and spatially, termed ‘mega-droughts’⁵¹, and it is these situations when interactions
194 with other hazards such as heat waves are strongest⁵².

195
196 The problem of interconnected hydrological drivers has prompted many advances in statistical
197 methods for compound events, including copulas and scenario modeling [see Table 2]^{15,53}. One
198 insight these have revealed is that, for droughts as well as floods, changes in the correlation
199 structure between drivers can alone lead to large changes in extreme events^{54,55}. Acting on this
200 awareness, agencies such as the U.S. Army Corps of Engineers have begun accounting for
201 correlations between river discharge and storm surge when planning coastal projects. The Corps
202 is also assessing the effects of sequential droughts and floods on reservoir operations, and of
203 post-fire precipitation on reservoir sedimentation.

204
205 Anthropogenic systems interact with the natural environment to direct and shape the ultimate
206 impacts of extreme hydrological events. For example, urban drainage systems modulate both the
207 amount of surface flooding and the water quality at discharge points, due to the correlation of
208 combined sewer overflows with heavy precipitation. In exceptional droughts, reservoirs used
209 primarily for water supply, flood mitigation, or power generation may actually worsen water
210 shortages and thereby tensions between different regions or water users⁵⁶. These physical-
211 societal dynamics lead to uncertainties in water-scarcity projections even larger than the
212 corresponding uncertainties in precipitation⁵⁷. Actions taken during an event can often be an
213 additional layer. During the spring 2011 Mississippi River floods driven by heavy rain and
214 snowmelt across the U.S. Upper Midwest, multiple spillways were opened (as designed) to
215 protect downstream urban areas, resulting in some flooding of agricultural lands⁵⁸. Similarly,
216 storm-surge barriers prevent ocean-side flooding when closed, but can worsen wave impacts on
217 the seaward side while simultaneously causing freshwater to accumulate on the landward side,
218 affecting areas that might not otherwise have been at risk, especially when rainfall-driven river
219 discharge is simultaneously high⁵⁹.

220 For both hydrological extremes, decisions made throughout a region have physical and
221 behavioral consequences which tend to accumulate over time and then be prominently manifest
222 when water becomes scarce or overabundant. The need to better understand and account for the
223 joint distribution of physical drivers and societal mechanisms warrants close collaboration
224 between social scientists, engineers, hydrologists, climate scientists, and water agencies —
225 encapsulated by the relatively new field of socio-hydrology⁶⁰.

226 *Health*

227 Population health is a function of a wide set of determinants, including interactions with multiple
228 environmental factors over time⁶¹. Where, when, and which populations are exposed to
229 connected extremes are all strong predictors of the severity of impacts⁶². Additionally,
230 demographic vulnerability is itself often multivariate and temporally compounding⁶³. For these
231 reasons, an integrated health perspective — considering wealth, insurance, housing, food
232 security, and other essentials — is gaining traction among researchers and practitioners. This
233 evolution makes the connected-extremes framework a natural one.

234
235 In the healthcare context, important types of compounding include multivariate extremes —
236 including heat/humidity and heat/air-quality events^{33,64} — and temporal compounding, on
237 timescales ranging from hourly-to-daily (for emergency response) to subseasonal-to-seasonal
238 (for preventative campaigns, supply-chain planning, and recovery efforts). For extreme heat,
239 diverse health hazards will very likely interact more frequently as the recovery time between heat
240 waves shrinks, making it a prototypical instance of a connection between extreme events
241 enhanced by climate change⁶⁵. Other societal drivers such as power outages, whether resulting
242 directly from physical drivers⁶⁶ or induced to prevent poorly maintained equipment from
243 sparking wildfires during compound wind and low-humidity events (such as in the 2019
244 California fire season), can also feed back onto health outcomes. These examples underscore
245 how human decisions made over decades modulate the health impacts of extreme events on
246 much shorter timescales.

247
248 Both knowledge and capacity for action pose challenges with regard to the impacts of connected
249 extreme events on the health sector. Many epidemiological analyses take limited advantage of
250 sophisticated methods for modeling these types of complex risks. Additionally, from the
251 operational point of view inherent to healthcare delivery, the motivation to adopt new tools and
252 methods — and to follow through on the ensuing recommendations — can be low in the face of
253 everyday demands, a lack of dedicated personnel, limited utilization of systems modeling, and
254 difficulties with funding for structural change. Health systems are diversely organized around the
255 world, with varying but typically limited coordination, information sharing, and inter-sector
256 collaboration⁶⁷. Although enhanced integration of disaster risk reduction, disaster preparedness,
257 and disaster response has the potential to manage risk more effectively, these activities remain
258 somewhat tenuously linked, with the result that the health sector is sometimes overwhelmed by
259 the impacts of connected extremes such as Superstorm Sandy (which was followed by a cold
260 Nor'easter) or Hurricane Maria. In these cases, personnel are not efficiently deployed, supply
261 chains are disrupted, and suboptimal health outcomes are achieved. Such crises have also spurred
262 improvements in organization and communications^{68,69}.

263
264 This situation creates an outsize need for improved quantification of and communication about
265 connected extremes with major potential health impacts, coordinated to align with and inform

266 specific procedural choices. For instance, while there have been some efforts to systematically
267 examine how connected extreme events may impact health systems⁷⁰, much more could be done
268 to determine where and how connected extremes may result in unanticipated impacts, such as by
269 drawing on past experiences⁷¹. The health sector could benefit from examples of how other
270 sectors have anticipated impacts and incorporated this learning into reforms.

271

272 *Infrastructure*

273 Critical infrastructure includes systems that provide energy, water, food, transport, and security.
274 Connected extremes can exert forces on these systems beyond their design specifications,
275 making it imperative to understand and incorporate such effects into infrastructure planning and
276 risk assessments. The relevant interactions are typically poorly constrained, despite the large
277 investments involved, due to the great complexities of the systems and the numerous and widely
278 disparate actors with jurisdiction over them.

279

280 Large wildfires and tropical cyclones, themselves sometimes compound events, frequently cause
281 flooding, slope failures, and vegetation blowdown, which in combination with vulnerable
282 infrastructure can impede emergency-response efforts and post-disaster rebuilding^{4,72}. Such
283 situations may also create unanticipated additional hazards such as major traffic jams⁷³. Well-
284 designed infrastructure can exhibit strategic purposeful failures which nonetheless result in
285 property damage or loss of life, as in the Mississippi River flood example above. Emergency
286 response and rebuilding efforts may be particularly vulnerable to sequences of extremes, such as
287 a heat wave following a hurricane⁶⁶ or wildfire-induced power outage.

288

289 Infrastructure decisions (investment, maintenance, and outreach) play a key role in connecting
290 extremes, especially for the most exposed or vulnerable communities. During the Thailand
291 floods of 2011, politically motivated decisions on how to route water resulted in the protection of
292 central Bangkok at the expense of peripheral areas, where major manufacturing facilities were
293 located⁷⁴. The resulting floods caused large economic losses in Thailand and globally, due to
294 supply-chain disruption that played out over the following months. At the dry end of the
295 spectrum, the pre-emptive California power outages cited above were deemed necessary due to
296 overgrown vegetation and aging equipment in addition to severe fire weather.

297

298 As a result, there is increasing adoption of systems thinking for infrastructure^{3,4} — considering
299 each subsystem’s design, management, and interconnections — but this requires climate
300 information of sufficient detail and reliability to be optimally employed. The interactions
301 described here highlight the necessity for more collaboration at the interface between natural
302 sciences, engineering, and social sciences, to enable policy choices that are well-informed,
303 robust, and equitable over the typically long lifetime of an infrastructure project.

304

305 *Insurance*

306 Insurance plays an integral role in risk management and disaster recovery for diverse sectors and
307 at scales ranging from personal to global. However, emerging spatial correlations across multiple
308 hazards of the same or different type could, if unrecognized, pose a systemic risk to re/insurers
309 and the broader economy.

310

310 Humanitarian and property impacts from large-scale disasters with multiple drivers (e.g., heat
311 and drought leading to wildfires) or multivariate hazards (e.g., wind and water for tropical

312 cyclones, or wind, hail, and water for severe convective storms) can be extremely costly (Figure
313 2). The earlier examples of Hurricanes Harvey and Maria in 2017, and the simultaneous
314 California wildfires in 2017 and again in 2019, are illustrative. The complexities associated with
315 recognizing and responding to such perils are amplified when the regions affected are
316 underinsured and/or repeatedly exposed⁷⁵⁻⁷⁷. Additionally, the global “protection gap” – the
317 portion of the economic cost of disasters not covered by insurance – is still a concern for
318 increasingly at-risk regions within Latin America, Africa, and Asia⁷⁸. Health-insurance coverage,
319 likewise, is strongly correlated with sociodemographic factors, creating another source of
320 inequality and population vulnerability.

321 The catastrophe models commonly used in the insurance industry are limited in their ability to
322 see connected multihazard events ‘over the horizon’ because they are calibrated using observed
323 or synthetically generated event sets and portfolio exposures. Event types that are known to be
324 possible but considered highly unlikely (‘gray swans’) are not well-captured in this framework,
325 precluding proper risk quantification. Even when connected events are able to be represented,
326 interpreting and acting on this knowledge remains challenging for re/insurers.

327 The overall risks associated with large, volatile, multivariate extreme-event impacts make it
328 essential for re/insurers and businesses to make decisions based on an accurate evaluation of the
329 hazards, which often means understanding the full spectrum of impacts of extreme events and
330 also the potential connections between them. Indeed, such connections may even threaten the
331 continued economic viability of corporations, insurers, and electric utilities that do not
332 sufficiently investigate them and act on this knowledge. The need to properly incorporate long-
333 term vulnerabilities from factors such as climate change and socioeconomic shifts poses a major
334 challenge to a business model where contracts are typically revised on an annual basis and thus
335 inherently short-term. As climate change progresses, assumptions regarding probabilities of
336 extreme events will need to be periodically updated, in addition to accounting for changes in
337 exposure and infrastructure vulnerability. Analyses and policies dependent on such updates will
338 necessarily contain greater uncertainty, with a smaller (or non-existent) comparable historical
339 record to refer to. Further collaborations that leverage the statistical expertise and computational
340 power of re/insurers and the scientific understanding and techniques of climate researchers have
341 large potential to illuminate this future more clearly⁷⁹.

342
343 ***Quantitative and conceptual methods***
344

345 Considering societal attributes and response capacities in addition to climate factors and
346 traditional impact models is a daunting challenge. However, targeted methodologies informed by
347 the particular type or location of impact can begin to decompose the complexity and diversity of
348 connected extremes. Some uncertainties surrounding the ‘event space’ of connected extremes
349 can be confronted with techniques aimed at constraining the underlying compound physical
350 drivers. We note a selection of these from the climate literature in Table 2 under ‘Statistical
351 Approaches’ and ‘Modeling Approaches’, and refer interested readers to refs. 8 and 13 for a
352 more complete description.

353
354 Disentangling the physical-societal interactions that characterize connected events, in contrast,
355 requires highly flexible and less-quantitative methods, to ensure usability and robustness in the

356 face of deep and complex uncertainties (Table 2, Socio-Physical Approaches section). For
357 instance, the adaptive-pathway approach⁸⁰ recognizes that the ‘decision space’ can be highly
358 sensitive to climate change, political or financial resources, or other contexts, and may exhibit
359 qualitative jumps at certain ‘tipping point’ thresholds⁸¹. Storylines and scenario-planning
360 methods about potential large-impact events allow for the engagement of stakeholders and the
361 public in identifying crucial factors, chains of causality, and ‘tail risks’ through a collaborative
362 process unencumbered by the usual focus on quantification^{71,82,83}. Stress testing explores the
363 ‘impacts space’ associated with connected extremes’ imprint on a given sector or location,
364 highlighting where impact sensitivities are largest in response to slight changes in physical
365 drivers^{84,85}.

366
367 In general, these approaches lead to fewer but more reliable conclusions than conventional
368 climate-impacts studies, especially for connected extremes with little or no precedent. Being
369 non-probabilistic, they require careful evaluation by sectoral experts to interpret their outcomes.
370 However, critical test levels can be associated with societal mechanisms, such as supply chains,
371 enabling assessment of the type and severity of extremes that could plausibly cause important
372 disruptions. Specific types of model validation and improvement which could further inform the
373 study of connected extremes include incorporating memory of how previous extremes have
374 affected risk through the depletion of resources, divergence of development pathways,
375 degradation of vulnerability, or alteration of exposure, and also better accounting for systemic
376 connections between regions and/or sectors through markets, resource pools, or decision-making
377 frameworks.

378
379 True coalescence around shared definitions, best practices, and research priorities can only occur
380 through sustained and in-depth conversations where sector experts, stakeholders, policy-makers
381 and practitioners meaningfully shape the research process from conceptualization to results to
382 implementation. This process has been described by many terms, including ‘co-production’^{86,87},
383 ‘joint problem formulation’⁸⁸, ‘co-development’⁸⁹, ‘design thinking’⁹⁰, and ‘bottom-up
384 approaches’¹¹. The underlying principles are consistent: to identify critical constraints and
385 interactions (from ethnography, expert solicitation, process-based impact models, and/or systems
386 analysis), and then to use these to iteratively formulate the questions that guide systematic study
387 of the climate. In our view, connected extreme events are too idiosyncratic to allow for a
388 prescribed ‘best’ approach *a priori*.

390 *Expecting the unexpected*

391
392 Systematic investigation of connected extremes is often limited by the quantity and type of
393 suitable historical data and model simulations, for both drivers and impacts. For example,
394 variables that play key roles in modulating many connected extremes (e.g., wind speed and
395 humidity) are not widely observed at fine temporal resolutions and have short periods of record,
396 but would greatly aid in observational analyses and model validations. In some regions, this
397 problem includes core variables such as precipitation. Essential vulnerabilities and interactions
398 between decision-making entities remain exogenous to most assessments of climate extremes, or
399 are not well-characterized at all, leading to uncertainties as basic as the primary cause of impacts
400 from historical connected extremes. Qualitative identification of connections can similarly be
401 limited by data availability. Resolving such questions would aid in building overall confidence

402 about how extreme impacts develop: which systems break down, why, and who is affected when
403 that happens.

404
405 The need for skillful forward-looking assessments is underscored by the rapidity of projected
406 21st-century warming, which will result in historical conditions always providing incomplete
407 information on the contemporaneous range of possibilities¹². Therefore, the coming decades will
408 no doubt see previously unanticipated or newly important combinations of extremes⁶⁶.
409 Additionally, risk relationships may change in a qualitative way, such as the emergence of
410 summertime drought-heat interactions in historically cool-summer regions⁵² or the increased risk
411 of compound flooding due to sea-level rise⁴⁵. Stretching the ‘event space’ in this way may result
412 in cultural, economic, ecological, and/or technological responses that reciprocally shape
413 exposures, vulnerabilities, and perhaps the anthropogenic forcing itself^{91,92}.

414 Climate-system knowledge that provides information about poorly constrained risks from
415 connected extreme events is crucial in helping determine the range of necessary actions.
416 Communication about such scenarios could be key for mobilizing all sectors of society to
417 consider their interfaces with other sectors and the ways in which these interactions cause them
418 to be at risk from connected extreme events. Tools and frameworks for assessing these risks
419 could therefore aid in making increasingly severe connected extreme events a central part of the
420 overall climate-change discussion, including via financial and legal mechanisms⁹³.

421

422 *Conclusions and recommendations*

423 The complex and contingent nature of connected extreme events causes them to possess several
424 attributes distinct from those associated with isolated or univariate extreme events. These include
425 a large, poorly characterized sensitivity to small changes in mean climate conditions and a low
426 availability of data on important physical and societal characteristics. Together, these lead to a
427 heightened risk of crossing unknown tipping points in terms of response capacity. Because
428 connection between extreme events depends heavily upon situational factors such as season,
429 location, and groups affected, careful impacts-oriented analysis, usage of higher-order metrics,
430 and collection of high-quality, high-resolution impacts data are essential for making progress in
431 addressing them. This is an area where the power of emerging computational and communication
432 technologies is likely to be keenly felt.

433 We consider the climate science community’s role as designing the research-side companion
434 element to the critical decision-making challenges associated with connected extremes⁸¹,
435 ensuring that scientific information is provided in a way that is congruent to existing decision-
436 making pathways^{86,94}. The bounds of the ‘decision space’ may significantly shape the roles of
437 scientists and decision-makers: problems with long-term aspects or a wide range of potential
438 policy solutions are most likely to be usefully informed by climate research, while actions with a
439 narrower scope and sensitive cultural or political considerations are weighted toward decision-
440 makers.

441 To the extent possible, collaborations should include determining major feedbacks between
442 physical processes and societal decisions that most affect the final impact. Stated differently,
443 impacts can serve as a winnowing device to identify what combinations of extreme events

444 matter. This knowledge-gathering can also incentivize the selection of a more-effective mix of
445 policies, including robust or flexible adaptation strategies that provide benefits under a range of
446 connected climate and impact outcomes, by better foreseeing relevant societal and environmental
447 changes over the timescale of the investment⁹¹. The ongoing COVID-19 pandemic represents a
448 dramatic object lesson in how unprecedented events can create or exacerbate correlated risks
449 related to both climatic and non-climatic stressors, amplifying impacts but offering opportunities
450 for shared learning and long-term resilience. Lastly, impacts-driven research efforts can reveal
451 particular disciplines where the presence of specialists would be especially valuable — there is
452 the potential for fruitful exchanges to take place between researchers in the climate domain and
453 experts in engineering, statistics, health, urban planning, sociology, psychology, finance,
454 ecology, and emergency management, among others. It is often only through such detailed
455 conversations that essential incentives and constraints come to light and that conceptual
456 paradigms shift⁹⁵.

457 Most broadly, we argue for promoting mechanisms to recognize the components of a connected
458 extreme event as such, and to gather and share important information about them to facilitate risk
459 management across all levels of decision-making. At a recent workshop, few participants knew
460 of any examples in which connected extremes had been included in planning guidelines. This
461 communication barrier also exists within the physical-science community, where examples
462 emerged of certain genres of events (e.g., local situations) for which the necessary resources
463 have not yet been gathered to examine the connectivity or full implications as might be seen
464 when looking through a wider lens. The strong modulation of the impacts of connected extremes
465 via complex societal systems demands serious and sustained efforts to facilitate geographic and
466 cross-domain knowledge exchange, such that climate research results can lead to well-informed
467 pre-event preparation and post-event recovery, ultimately aiding in the amelioration of the
468 serious impacts that connected extremes often produce. Facing this challenge, some
469 encouragement might come from the analogous example of aviation, where physical science,
470 engineering, and social sciences have come together to successfully mitigate — despite greatly
471 increasing system complexity — the frequency of disastrous failures which tend to result only
472 from the concatenation of many low-probability events.

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Figures

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Table 1: Climate-related hazards with compound physical drivers as well as exacerbating societal drivers			
Hazard(s)	Climatic Drivers	Societal Drivers	Ref.
Drought	Precipitation, evapotranspiration, antecedent soil moisture, temperature	Water management, land-use change	48, 49, 56
Physiological heat stress	Temperature, atmospheric humidity, diurnal cycle	Urbanization, irrigation	96
Fire risk	Temperature, precipitation, relative humidity, wind, lightning	Forest management, ignitions	97, 98
Storm risk	Wind speed, humidity, large-scale atmospheric circulation	Urbanization, deforestation	99
Coastal flooding	River flow, precipitation, coastal water level, surge, wind speed	Hard infrastructure, removal of natural coastal barriers	100, 101
Flooding at river confluences	Precipitation, river water levels, large-scale atmospheric circulation	Water management, urbanization	58
Concurrent heat and drought	Temperature, precipitation, evapotranspiration, atmospheric humidity	Water management, soil management, land-use change	48, 49
Concurrent wind and precipitation extremes	Wind speed, precipitation, orography, large-scale atmospheric circulation	Few or none	75
Concurrent heat and air pollution	Temperature, solar radiation, sulfur dioxide, NO _x , ozone, particulate matter	Urbanization, agricultural and industrial activities	99

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Table 1: Examples of how compounding climatic drivers and societal drivers interact to produce connected climate extremes, modified from Table 1 of ref. 9. The societal drivers listed are non-exhaustive; additionally, only those that contribute directly to the hazard are considered, rather than those that contribute to the impact. Long-term anthropogenic climate change plays into many of these hazards, but is omitted here for simplicity. References are for societal drivers only (for climatic-driver references, see ref. 9).

Table 2: Methods for investigating connected extreme events and their impacts				
Statistical Approaches	Description	Strengths	Weaknesses	Ref.
Copulas	Characterizes dependence among multivariate physical hazards or drivers	Common and well-developed; straightforward to apply	Limited data can make fitting difficult; does not identify causal relationships	53, 102
Event-coincidence analysis	Counts simultaneous extreme events across timeseries	Simple framework for assessment of simultaneity	Requires clear event definition; generally limited to two timeseries; does not identify causal relationships	37, 103
Complex networks	Identifies interacting extreme events with a dynamic lead-lag	Can reveal lagged and indirect relationships otherwise hidden	Computationally intensive; interpretation requires deep system knowledge	104
Modeling Approaches	Description	Strengths	Weaknesses	Ref.
Large climate model ensembles	Physical models produce thousands of years of simulations	Large sample size can include directly modelled rare events beyond those in the historical record	Model representations of extreme events and inter-relationships may not be accurate	105
Hazard, catastrophe, and statistical-dynamical models	Generate large numbers of synthetic events for any climate scenario	Can be coupled with impact models; less computationally intensive than climate models	Model representations of extreme events may not be accurate; sensitive to datasets of limited size	79, 106, 107
Integrated assessment models	Model a wide range of societal impacts resulting from climate-related risks	Incorporate many sectors and interactions	Generally have coarse spatial resolution and simplified interactions (e.g., no two-way feedbacks)	108
Socio-Physical Approaches	Description	Strengths	Weaknesses	Ref.
Adaptive pathways	Explore specific possible futures and sequences of adaptation responses	Allow for policy planning despite uncertainties of future climate change	May require many assumptions about future pathways	80, 109
Storylines and scenario planning	Explore sequences of events, impacts, and associated decisions independent of probability	Enable identification of high-impact combinations of events that probabilistic assessments might miss	May require many assumptions about future scenarios	71, 82
Stress testing	Explores the	Highlights weakest links in	May require expert	84,

	performance of a complex system during extreme events	interconnected societal systems	knowledge to identify the climate variables to which the system is most sensitive	85
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Table 2: A selection of methods relevant for connected extreme events and their impacts, representing a snapshot of the diversity of each type of approach. References are intended to provide a guide as to how the methods are used. In many cases, a combination of different methods is necessary to understand the drivers, impacts, and future projections of connected extreme events.

Figure Captions

Figure 1: The flow of connected extremes. (a) Generalized diagram of the interactions among physical and societal drivers that constitute connected extreme events. Boxes 2 and 3 together represent ‘risk’ as defined in the text. (b) An illustration of (a) for the case of Hurricane Maria impacting Puerto Rico in 2017 following a sequence of severe tropical cyclones in the Caribbean and Gulf of Mexico. For simplicity, only one or two examples in each category are presented. In Box 3, TX refers to the state of Texas. References: Box 1: behaviors¹¹⁰, territory status²⁰, building codes⁴, grid upkeep⁴, government budgets³, communications systems⁴. Box 2: isolated mountain towns²¹, aging power system²⁰. Box 3: Maria¹, Harvey¹¹¹. Box 4: flooding and treefall²¹. Box 5: mortality²¹, infrastructure damage⁴. Box 6: rebuilding of infrastructure²⁰, policy changes⁴. Arrows: FEMA mismanagement²², rebuilt drainage systems²⁵, future extreme-precipitation increases¹¹¹, location and quality of rebuilt systems⁴, personnel, supplies, and information²³.

Figure 2: Major losses caused by extreme climate events over 1980-2019 and their connective elements. Lines trace the annual global sum of estimated economic losses caused by tropical cyclones (green), floods (blue), droughts (brown), and wildfires (red). Annotations indicate the largest events in high-loss years, followed by several of the (first row) physical and (second row) societal drivers that shaped the total impacts. Economic-loss data are from Aon, Catastrophe Insight Division.

Figure 3: Decisions related to multiscale connected extremes. Generalized diagram of the spatiotemporal scales associated with connected extremes (across both physical and societal aspects) compared against the typical spatiotemporal scales of the decision-making that affects the societal response to them, for two example events and two example actors. The meters for each actor indicate their (hypothetical) relative characteristics in terms of technical capability (T), cultural or political capital (K), and financial or geographic size (S). High meter readings correspond to a capacity for broad, complex, long-term, and expensive actions, whereas low meter readings correspond to a necessity for taking localized, simpler, short-term, and less-expensive actions.

532

533 **Box 1: Connected extremes definition and conceptual framework**

534

535 **Defining connected extreme weather and climate events**

536 Compound weather and climate events are comprised of multiple distinguishable physical
537 drivers and/or hazards and their risks. These can be subdivided according to the primary means
538 of interaction: temporal compounding (e.g., a sequence of storms), spatial compounding (e.g.,
539 synchronous crop failures), preconditioning (e.g., rain-on-snow flooding), and concurrence of
540 multiple variables (e.g., storm surge, pluvial flooding, and high winds from a single storm).
541 Details on these categories can be found in ref. 8.

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543 The concept of connected extreme weather and climate events further recognizes that compound
544 event impacts are often substantially, nonlinearly influenced by non-physical factors such as
545 exposure and vulnerability, cutting across sectors and scales (from personal to society-wide).
546 These ‘societal mechanisms’ can tie together the impacts from two or more climate extremes,
547 whether due to resource constraints (e.g., exhaustion of an insurance fund or pool of emergency
548 responders), health considerations (e.g., power outages or medication-supply-chain disruptions),
549 or other linkages (Figure 1). Other possible longer-term feedbacks range from changes in risk
550 pricing to wholesale rethinking of risk-management strategies³⁰, which in Figure 1 are
551 compressed into the ‘Response’ category. Whatever their nature, connections’ meaningfulness
552 lies in their robustness and traceability, terms which can only be defined by the stakeholders
553 involved.

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555 It is the creation or strengthening of the connections between events, in the impacts space and
556 involving anthropogenic systems, that leads to our terminology of ‘connected’ events as being
557 distinct from ‘compound’ events, and also from interacting-risk or multi-risk frameworks that
558 focus on combinations of physical hazards¹³.

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560 **A challenge of ‘spaces’**

561 One framework for understanding the research and decision-making issues associated with
562 connected extremes is to view them as resulting from a mismatch between the planning and
563 response decisions that would be achieved by conventional methods (the ‘decision space’) and
564 those that would optimally address the full set of physical possibilities (the ‘event space’) (Figure
565 3). Many organizations are constrained to make decisions within a narrow spatiotemporal
566 domain, leading to conflicting decisions at one scale versus another. A small city with a limited
567 budget (represented by Actor 1 in Figure 3), or a government agency with a specific mission,
568 cannot be expected to have the capacity to coordinate across multiple spatial scales to optimally
569 plan for or respond to multivariate or sequential connected extremes which fall only partially
570 under its purview, much less spatially compounding extremes like river flooding caused by
571 conditions upstream. Additionally, physical processes and data availability make the event space
572 difficult to reliably estimate — a confounding uncertainty when trying to reach a decision under
573 political, financial, and technical constraints^{95,112,113}.

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575 Major wildfires, for instance, are often ‘connected’ in several ways⁹⁷. Actors such as city
576 departments, national agencies, private landowners, insurers, corporations, and nonprofits must
577 decide how to manage long-term fire risk, emergency responses, and recovery, including

578 decisions about how and where to reinvest. Each of these spheres of action is guided by (1) the
579 size and mandate of the decision-makers, which defines their mission and hence affects their
580 quantity of resources, (2) their ability and/or incentive to distribute risk, and (3) the political
581 expectations or regulatory requirements under which they operate. These diverse incentives and
582 restrictions complicate efforts to plan and execute a holistic response that does not, for example,
583 merely delay the risk or transfer it to other sectors⁹⁵. Hence, understanding this patchwork of
584 'decision spaces' can aid in characterizing the type of decision-relevant knowledge that research
585 on connected extremes should aim to generate. Social scientists, risk managers, and boundary-
586 spanning organizations are indispensable here, by helping to build and leverage communication
587 networks that can delineate the feasible intersection of the decision and event spaces.
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614 C.R., R.M.H., J.Z., and O.M. developed the initial concept. C.R. created figures and S.G.B.
615 provided data for Figure 2. C.R. led the writing of the manuscript, and all authors contributed to
616 writing and editing.

617
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619
620 **Competing Financial Interests**

621 The authors declare no competing interests.

622
623 **Data Availability**

624 Data used in Figure 2 are available from the corresponding author upon reasonable request. The
625 data are not publicly available as they are part of a commercially proprietary dataset.

626
627 **Code Availability**

628 Code for reproducing Figures 2 and 3 has been archived at
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630
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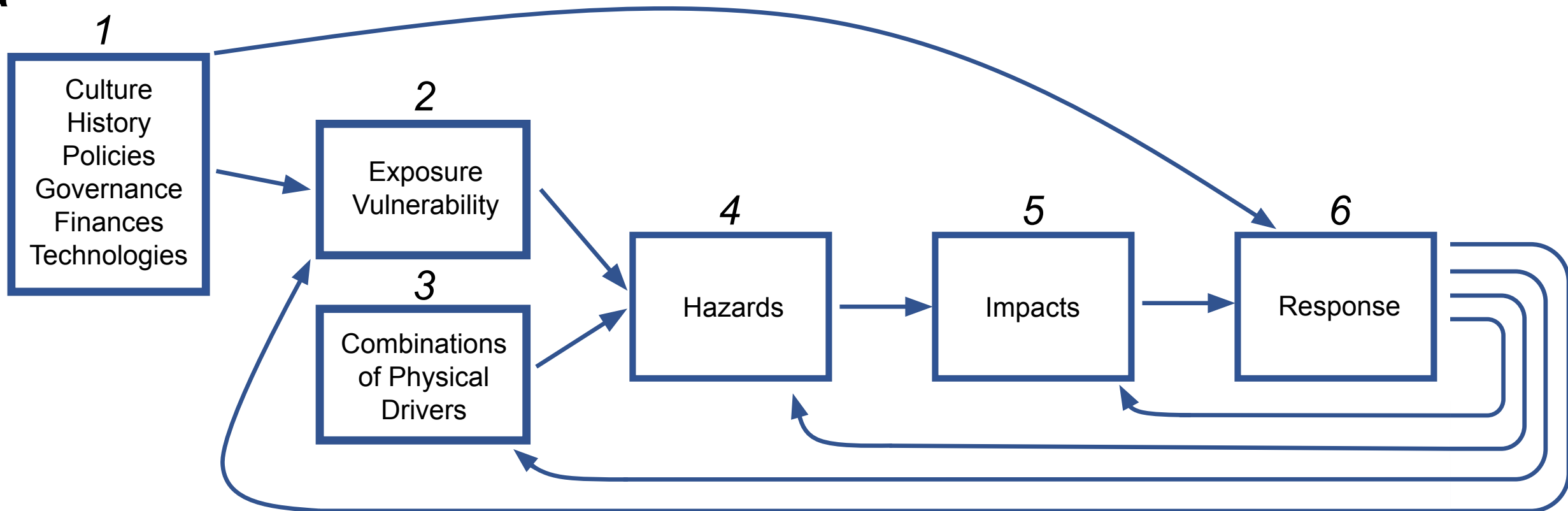
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