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PERSPECTIVE

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Future climate risk from compound events

Jakob Zscheischler[1*], Seth Westra[2], Bart J. J. M. van den Hurk[3,4], Sonia I. Seneviratne[1], Philip J. Ward[4], Andy Pitman[5], Amir AghaKouchak[6], David N. Bresch[7,8], Michael Leonard[2], Thomas Wahl[9] and Xuebin Zhang[10]

Floods, wildfires, heatwaves and droughts often result from a combination of interacting physical processes across multiple spatial and temporal scales. The combination of processes (climate drivers and hazards) leading to a significant impact is referred to as a 'compound event'. Traditional risk assessment methods typically only consider one driver and/or hazard at a time, potentially leading to underestimation of risk, as the processes that cause extreme events often interact and are spatially and/or temporally dependent. Here we show how a better understanding of compound events may improve projections of potential high-impact events, and can provide a bridge between climate scientists, engineers, social scientists, impact modellers and decision-makers, who need to work closely together to understand these complex events.

In the summer of 2010, Russia was struck by an unprecedented heatwave[1]. Below-normal precipitation in the first seven months of the year induced a summer drought that contributed to the exceptional magnitude of the heatwave[2]. The extremely dry and hot conditions led to widespread wildfires[3], which damaged crops and caused human mortality[4]. The wildfires also induced large-scale air pollution in cities such as Moscow[5], adding to the death toll caused by the heatwave[6]. The incidents in Russia in the summer of 2010 can be termed a compound event, involving the co-occurrence of multiple dependent hazards: drought, heat, fire and air pollution. In combination, these hazards caused devastating impacts in many areas, at a scale well beyond that which any one of these hazards would have caused in isolation.

One might think that the simultaneous occurrence of these hazards is bad luck or simply a low-probability occurrence. Indeed, the extraordinary nature of the 2010 event in western Russia is clear and could be viewed as too rare to be predictable. However, accounting for dependencies between all relevant climate drivers and/or hazards increases the likelihood of such events considerably, and may make events of the rarity of the Russian event foreseeable and to some extent predictable, as illustrated in the following. Temperature and precipitation are strongly negatively correlated in summer over western Russia, increasing the likelihood of extremely hot and dry summers by a factor of up to five compared with both variables being independent[7]. Furthermore, in addition to rising global temperatures[8], low soil moisture in spring and summer strongly increased the magnitude of the heatwave[2], providing an opportunity for increased predictability. Similarly, fire regimes are known to interact closely with drought[9], and high temperatures and low humidity can be predictable precursors of intense fires[10].

The interaction between multiple climate drivers and/or hazards can also play a major role in coastal extremes[11,12]. Hurricane Sandy hit the metropolitan New York area in 2012, causing damages in excess of US$50 billion and a total death toll of 233[13]. Sandy's significant impacts were due to its unusual path, which resulted from multiple weather systems coinciding over the North American continent and the north Atlantic. Atlantic hurricanes commonly dissipate over the open ocean; however, a strong blocking high in the mid- to high latitudes of the north Atlantic in combination with a mid-latitude trough over Canada and the northeast United States steered Sandy back towards the coast[14], leading to substantial inland rain and flooding. Coming almost directly from the east, the storm caused the highest storm surge in at least 300 years[15], and coinciding with a high (spring) tide, the storm led to widespread flooding in New York City and surrounding areas. The strong winds also produced high waves along the sandy coasts of New Jersey, where they could travel closer to shore without breaking because of the high water levels from the storm tide, ultimately resulting in massive coastal erosion[16]. The compounding effects from inland precipitation (pluvial flooding), high wind speeds, storm surge and waves, played an important role in exacerbating the impacts of the event.

In 2017 Hurricane Harvey provided another example of compound flooding. From a meteorological perspective, the simultaneous occurrence of a high-pressure system over the western United States pushed the storm back into the Gulf of Mexico instead of allowing it to follow the typical track further inland, where the system would have dissipated much faster. Instead, Harvey circled back and made landfall a second time in the greater Houston area. The stationarity of the system for an extended period of time led to extremely high accumulated precipitation over several days (initial estimates suggest a return time between 100 and 2,000 years[17]). At the same time, Harvey produced a storm surge along the coast that was moderate in height, but affected an extremely long segment of the coast, with elevated water levels over five days and multiple tidal cycles, significantly reducing the inland freshwater drainage capacity. From a climate perspective, unusually high sea surface temperature additionally fuelled the tropical system[18], and sea-level rise has led to higher baseline ocean levels than a century ago. This

[1]Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland. [2]School of Civil, Environmental and Mining Engineering, University of Adelaide, Adelaide, South Australia, Australia. [3]Royal Netherlands Meteorological Institute (KNMI), De Bilt, The Netherlands. [4]Institute for Environmental Studies, Vrije Universiteit Amsterdam, Amsterdam, The Netherlands. [5]Australian Research Council Center of Excellence for Climate Extremes and Climate Change Research Center, University of New South Wales, Sydney, New South Wales, Australia. [6]Department of Civil and Environmental Engineering, University of California, Irvine, CA, USA. [7]Institute for Environmental Decisions, ETH Zurich, Zurich, Switzerland. [8]Federal Office of Meteorology and Climatology, MeteoSwiss, Zurich, Switzerland. [9]Department of Civil, Environmental and Construction Engineering and National Center for Integrated Coastal Research, University of Central Florida, Orlando, FL, USA. [10]Climate Research Division, Environment and Climate Change Canada, Toronto, Ontario, Canada. *e-mail: jakob.zscheischler@env.ethz.ch

highlights the range of spatial and temporal scales that can ultimately lead to the extreme impacts: from long-term global warming changing the background climate state, through to the occurrence of Hurricane Harvey causing heavy wind and rain and finally to the localized effects in terms of storm surges and flood events for Houston and the surrounding area.

Extreme events with devastating impacts such as those described above leave an imprint in public memory and are typically characterized by a complex chain of processes, often extending well beyond the local event itself. The destruction of large amounts of Russian crops led to a grain export ban until the end of 2010, affecting global wheat prices[19] and potentially contributing to instability and uprising in Egypt[20]. Parallel to the Russian heatwave, a record-breaking flood occurred in Pakistan, which affected more than 20 million people[21]. There is strong evidence that these features are connected through atmospheric dynamics[22].

Understanding compound events therefore requires an analysis of the complex causal chains that can lead to extreme impacts. Multiple drivers and/or hazards have to be investigated because it is their combination that renders an event exceptional and pushes the impact to extreme levels. In many cases, however, the unusual combinations of processes associated with the events makes them difficult to foresee, in particular because they are so rare and may not have observed historical analogues[23]. This issue is likely to be exacerbated as a result of climate change and human activity affecting both the background climate state[24,25] and how the system functions. Therefore, the historical record of compound events provides incomplete information on how events may occur in the future. Furthermore, as we consider more complex causative changes, the likelihood that specific combinations and sequences of drivers and/or hazards have occurred previously can rapidly approach zero[26]. Apart from changing likelihoods of the contributing processes, systematic climate change has the potential to change relationships between drivers and hazards to create novel conditions that our socioeconomic systems have not been designed to withstand[27].

Multiple drivers, conditional dependencies, a complex chain of processes and extreme return times; these are all characteristics of extreme climate events that lead to devastating impacts. Common practice based on highly idealized conceptual frameworks of modelling, scenario construction and statistical analysis each have difficulties in fully capturing these interrelationships. Given their disproportionate impacts, however, improving our understanding and modelling capabilities of such events is of crucial importance.

In this Perspective, we first introduce a new definition of compound events, which aims to establish a framework for compound event research. We then argue that a paradigm shift is needed when compound events are incorporated in climate impact analysis. We further discuss how compound event research can improve risk assessments of extreme events. We end with five recommendations targeted to the climate science and impact modelling communities to advance compound event research.

Defining compound weather and climate events

A particular challenge with understanding compound events is that dependencies between drivers and/or hazards can make the estimation of event probabilities more difficult than if all drivers and hazards were independent[28,29]. Poor representation of these dependencies can lead to an underestimation of the risk of catastrophic impacts, given that risk is often much greater than a naive independent combination of the individual components would suggest[7,12,30–32]. For instance, extreme storm surge and rainfall events are often positively correlated along the coastlines of the United States[12], The Netherlands[32] and Australia[33], increasing the probability of coastal floods. Precipitation and wind extremes are also likely to co-occur, augmenting the risk of infrastructure damage during severe storms[34]. Likewise, because of land–atmosphere feedbacks[35], warm season temperature and precipitation are generally negatively correlated, rendering an extremely hot and dry summer far more likely than an extremely hot and wet summer[7]. Table 1 presents a non-exhaustive list of climate and/or weather driver combinations that can lead to hazards, and hazards combinations that are known to cause large impacts.

Table 1 | Non-exhaustive list of documented climate-related hazards for which drivers are dependent as well as combinations of dependent hazards with potentially large impacts

Hazard(s)	Climatic drivers	Reference(s)
Drought	Precipitation, evapotranspiration, historic evolution of soil moisture, temperature	35,77,78
Physiological heat stress	Temperature, atmospheric humidity, strongly dependent on diurnal cycle	56
Fire risk	Temperature, precipitation, relative humidity, wind, lightning	55,79
Storm risk	Wind speed, humidity, large scale atmospheric circulation	94,95
Coastal flood	River flow, precipitation, coastal water level, surge, wind speed	11,12,30
Flood risk at river confluences	Precipitation, water levels of contributing rivers, large-scale atmospheric circulation	31
Concurrent drought and heat	Temperature, precipitation, evapotranspiration, atmospheric humidity	7,35
Concurrent wind and precipitation extremes	Wind speed, precipitation, orography, large-scale atmospheric circulation	34
Concurrent heat and air pollution	Temperature, sulfur dioxide, NO_x, particulate matter (PM_{10})	6,76

Given that most previous climate-related studies of hazards focus on single drivers, and given the evidence that the events that are particularly worrisome are typically multivariate in nature as illustrated by the examples in this manuscript, we encourage a deeper focus on multivariate drivers and hazards of large climate-related impacts. We therefore introduce the following definition.

Compound weather/climate events. We here define compound compound weather/climate events as the combination of multiple drivers and/or hazards that contributes to societal or environmental risk (Box 1). Drivers include processes, variables and phenomena in the climate and weather domain that may span over multiple spatial and temporal scales. Hazards are usually the immediate physical precursors to negative impacts (such as floods, heatwaves, wildfire), but can occasionally have positive outcomes (for example, greening in the Alps during the 2003 heatwave in Europe[36]). Risk is defined as probability of hazards (events or trends) × consequences (see Box 1 for definitions used in this Perspective). In the simplest case, × represents multiplication[37], but more generally, it represents a convolution of the respective distributions of probability and consequences. In that sense, integrating over a limited range that only includes highly frequent low-impact events can result in risks that are comparable to the risk associated with very rare high-impact events[38]. Furthermore, in the tail of the event distribution, which is often associated with the most catastrophic impacts, probabilities may not be quantifiable and storyline approaches[39] are needed.

Box 1 | Definitions used in this Perspective

Risk. The "effect of uncertainty on objectives"[97]. According to the IPCC[96], risk is the potential for consequences when something of value is at stake and the outcome is uncertain, recognizing the diversity of values. Risks arise from the interaction between hazard, vulnerability and exposure and can be described by the formula:

$$\text{Risk} = (\text{probability of events or trends}) \times \text{consequences}$$

where consequences are a function of the intensity of hazard (event or trend), exposure and vulnerability. Here, we use the term risk to refer to environmental and societal impacts from weather and/or climate events.

Exposure. The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected[96,98].

Vulnerability. The propensity or predisposition to be adversely affected[96,98]. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

Hazard. The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources[96]. Here, the term hazard usually refers to climate-related physical events or their physical impacts.

Compound weather/climate events. The combination of multiple drivers and/or hazards that contributes to societal or environmental risk.

Weather and climate events. Events at spatial and temporal scales varying from local weather to large-scale climate modes.

Drivers. These include climate and weather processes, variables and phenomena. We refer to the term drivers throughout as direct (climate and weather related) causes of climate-related hazards.

Impacts. The effects of physical events on natural and human systems[96].

Compound events can be embedded in the general risk framework linking hazards, vulnerability and exposure (Fig. 1). Changes in exposure and vulnerability, often related to human development[40], can strongly affect environmental risk. While we acknowledge this contribution, we focus on climate-related hazards here.

Our definition of compound weather/climate events generalizes the earlier definitions in the IPCC Special Report on Climate Extremes (SREX)[41], which introduced compound events as a general concept to the climate sciences, and that of Leonard and colleagues[28], who suggested a definition of compound events that refers only to extreme-impact events with dependent drivers. Our definition aims to establish a clear framework for ground-breaking research in the climate and impact science communities.

A paradigm shift in climate impact analyses

The emphasis on combinations of drivers and/or hazards that lead to societal or environmental risks highlights the importance of understanding the nature of the risks before identifying the relevant drivers and hazards. This suggests the use of bottom-up approaches to help identify which drivers and/or hazards lead to large impacts. Bottom-up approaches[42] usually start with a system or impact (such as a disaster), and then identify all of the underlying variables, processes or phenomena that play a role in shaping the outcome. This includes identifying which parts in the driver distribution lead to large impacts, and is therefore highly appropriate for studying compound weather and climate events. For instance, understanding the possible meteorological drivers of a power outage in a city might require identification of the climate-sensitive elements of the energy system, such as the combination of renewable resources (solar, wind and hydroelectricity), together with the physical assets such as poles and power lines that could be affected by heavy winds, lightning and flooding. This in turn forms the basis for understanding the weather and/or climate drivers and hazards that could influence that system.

This system-centric approach contrasts with top-down or scenario-led approaches[43–45], whereby climate change scenarios are generated using climate models and then incorporated into an impact model. So far, potential impacts of climate extremes are predominantly assessed via top-down approaches. In this way, flood risk[46] as well as impacts on crop yields[47] and human health[48] have been estimated based on individual drivers and/or hazards or an (independent) combination of multiple drivers such as run-off, temperature and precipitation. Top-down approaches require bias correction and downscaling[43], resulting in large increases in uncertainty[45], while their effects on the multivariate distribution of climate drivers and/or hazards are unknown. Furthermore, future climate scenarios do not cover the full probability space of all possible future conditions[49,50]; hence, such risk assessments are unlikely to represent the 'real' risk. It is therefore unclear how well top-down approaches capture impacts associated with multiple interacting drivers and/or hazards.

The benefits of the bottom-up approach for compound events is that it focuses attention on the combinations of drivers and/or hazards that can cause a system to fail, and then works backwards to identify lines of evidence that could provide insights into the likelihood of such combinations. Bottom-up or 'scenario-neutral' approaches are therefore increasingly being used to understand climate impacts and system resilience[42,44,51–53]. The shift from top-down to bottom-up approaches is in essence comparable to the shift from impact analysis to vulnerability analysis in socio-economic studies of climate change risks[54]. Whereas impact analysis traces the impacts of a single hazard (drought) to multiple outcomes (famine, economic loss), vulnerability analysis characterizes the multiple causes (low precipitation, poverty, lack of planning) of single outcomes (famine).

An additional advantage of bottom-up approaches is the potential for studying the impacts of hazards and the climate drivers of those hazards in separation. This is an effective way to study multiple hazards and their driving mechanisms simultaneously. At the same time, it avoids a biased view by focusing on the full distribution of climate drivers instead of only the fraction that is relevant for a particular hazard. This may turn out to be very effective, as different hazards based on the same set of drivers may vary along different gradients in the climate driver space (Fig. 2). For instance, the Chandler Burning Index (an index for fire risk[55]) and wet-bulb temperature (an index for heat stress[56]) can both be expressed in terms of temperature and relative humidity[55,57]. While dry and hot conditions increase fire risk (Fig. 2a), dry and humid conditions increase human mortality risk (Fig. 2b). As illustrated by this example, the distribution of the climate drivers of a given hazard is in principle independent of the direction in which the hazard intensity varies,

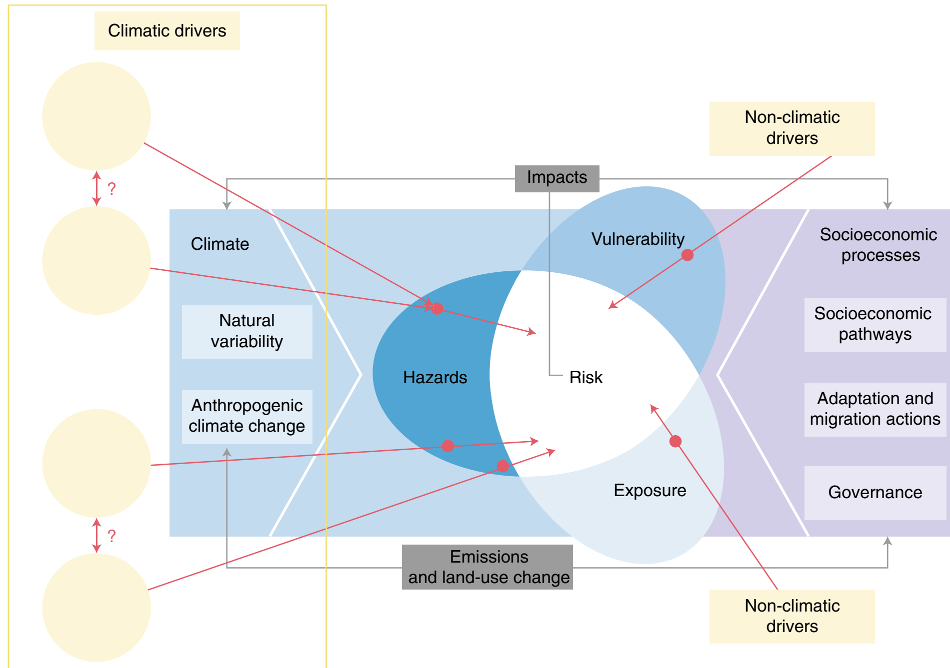

Fig. 1 | Extended risk framework. Multiple climatic drivers cause one or multiple hazards leading to societal and environmental risk. The climate drivers (which may vary from local-scale weather to large-scale climate modes, represented by yellow circles) and/or hazards may be mutually dependent. Non-climatic drivers related to vulnerability and exposure may also contribute to risk. Background risk figure adapted from ref. [96], IPCC.

supporting a separate analysis of hazards and drivers. Moreover, the multivariate distribution of climate drivers may change over time, for instance if one driver is affected by trends[25,58] (temperature increase, sea-level rise[59], trends in storm activity) or changes in the distribution (changes in temperature variance[60], shifts in precipitation distribution[61]). Finally, the dependence between climate drivers may change over time, which also affects the multivariate distribution of drivers. For instance, the increase in concurrent extreme storm surge and precipitation events for United States coasts has been attributed to changes in the dependence between surge and precipitation rather than to trends in either of these variables[12]. Similarly, the dependence between summer temperature and precipitation is expected to change under strong GHG forcing[7]. Note that even if we can model the whole distribution of drivers or hazards based on observational data, estimating dependence in the tails[62], for instance between different hazards, may still be challenging if the sample size is not very large.

Identifying which multivariate constellations of climate variables are associated with hazards allows climate model output to be interrogated for exactly these constellations. Assessing the likelihood of such constellations in future projections will help to investigate risk. Besides providing a tool for the assessment of hazard likelihoods, this approach will bring focus on those physical processes that need to be better understood to represent hazards in dynamical models, providing guidance on which variables and dependencies between variables need to be simulated skilfully or bias-adjusted[63] to correctly quantify hazards. The impact research community and the climate science community can both contribute to this effort by working closely together, revising and integrating currently used approaches and moving towards a multivariate perspective in all compartments of model construction, bias adjustment and analysis.

Climate change processes and associated effects

The bottom-up approach helps to define the required scope of the modelling of physical processes that give rise to a particular compound event. How can we represent these processes adequately? While spatial and temporal scales of compound events can vary significantly, the impacts are commonly felt at the local scale over relatively short timescales. However, local-scale events are often embedded within larger-scale systems, which in turn are affected by planetary-scale features such as shifts in the radiation balance and associated changes in mean temperature, mean sea level, the location of the jet stream and others. Modelling approaches that represent these ranges of space and time scales are therefore needed. The non-stationarity of most compound events — both because of anthropogenic climate change and because of other more local-scale changes in the land surface due to urbanization and other forms of development — has significant implications for how compound events should be modelled.

These implications can be understood through the example of estimating the probability of flooding for a particular catchment. In the past, if historical records of sufficient length were available, it was common to use these records to estimate the exceedance probability of a future event through a method called flood frequency analysis. However, such methods are only appropriate when the climatic drivers of floods are stationary over time. Flood frequency analysis is not appropriate as a basis for designing future infrastructure under considerations of significant climate change, since the historical statistics may no longer reflect flood hazard in the future. This means that to estimate the probability of flooding, we need to understand the nature of changes affecting extreme events much more explicitly, leading to a widening of the system boundaries. For many event-based hydrological models, antecedent moisture conditions are typically treated as calibration parameters, for example through loss parameters of the hydrological model. However, under future climate, extreme rainfall may increase at a faster rate than average rainfall, and evapotranspiration may change as well, so that the relationship between flood-producing rainfall and the catchment's antecedent conditions is no longer stable and may need to be modelled explicitly, for example by using a continuous hydrological

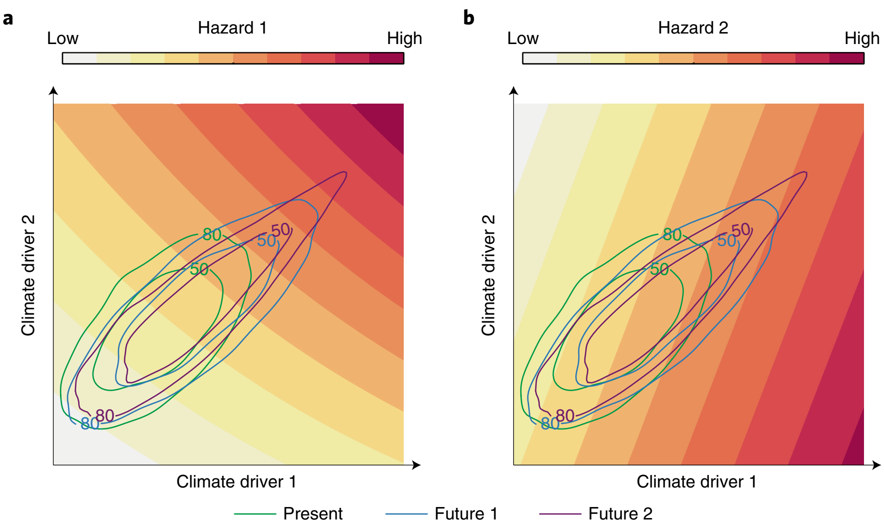

Fig. 2 | Distribution of climatic drivers and associated hazards. a, The hypothetical distribution of two climatic drivers in the present climate (green), a future climate with a shift in mean, variability and correlation between the drivers (Future 1, blue) and a future climate with an increase in dependence in the upper tail of both drivers (Future 2, purple). The intensity of Hazard 1 increases towards the upper right of the climate space. This could be, for instance, human heat stress if the climate drivers are temperature and humidity. **b**, The same climate distributions as in a for Hazard 2, which increases towards the lower right of the climate space. This could, for example, represent fire risk. Contours show the 50th and 80th percentiles, colour coded by climate.

model[64]. Human activity may further complicate the picture[65]. This example illustrates that as more aspects of a system change, the boundaries of system models must necessarily become wider, leading to a greater need to consider dependencies between interacting processes and an associated increase in modelling complexity[66].

Improving modelling capacities for compound events in a changing environment requires a good understanding of the physical processes that lead to such events. The simulation of compound events requires climate models to skilfully reflect both the mean state and natural variability, probably with a higher degree of skill than is currently achieved by regional and global climate models[67]. Improving the overall mean state and variability of global climate models is extremely challenging, but ways forward have already been broadly identified[68,69]. In addition, compound events that are related to weather-scale phenomena need to be studied by climate models that resolve those scales. This will necessitate models with much higher resolutions[70], close to at least 20 km, with major implications for parameterizations, computational demands and data management. It is unlikely that these requirements can be met by a simple business-as-usual approach to climate modelling. Efforts by the World Climate Research Program such as the Grand Challenge on Weather and Climate Extremes and the High Resolution Model Intercomparison Project[71] are designed to move the community forwards to address this challenge by encouraging a focus on climate, and climate modelling, at higher spatial resolutions that resolves small-scale high-impact phenomena. Close collaboration between climate modellers and the numerical weather prediction communities on applications such as conditional ensemble sampling and sophisticated post-processing may result in powerful tools to produce credible heavy weather warnings.

The quality of modelled future climate trends cannot be evaluated against observations. Like all future projections, confidence in the simulations of compound events for future conditions needs to be assessed by the model's ability to accurately reproduce physical processes and their interactions for current climate conditions[72]. Hazeleger and colleagues[43] suggest the use of numerical weather prediction modelling systems, which are confronted with observations and consequently updated and improved on a routine basis. Evaluation of these modelling systems with observations thus needs to include an analysis of the physical and statistical features of the compounding elements that emerge in the simulations.

Risk assessments and projections

A good understanding of processes that lead to extreme events is paramount for providing reliable risk projections under climate change. Climate change studies typically focus on distributions of univariate quantities of relevant climate extremes in hazard projections[73]. These quantities include the hottest or coldest day of the year, changes in the frequency of heat waves, drought magnitude, extreme precipitation and flood occurrence. A list of predefined indices facilitates this type of hazard projection[74]. However, impacts are often related to multiple drivers[75,76]. If univariate hazard measures[55,56,77–79] from these multiple drivers are not readily available or cannot be derived, the dependence between the drivers has to be incorporated into the risk assessments, because otherwise risk probabilities may be biased[7,11,29,80]. For instance, the likelihood of compound precipitation and wind extremes strongly varies over land depending on the interaction of weather regimes and topography[34]. Studies on projections of extremes also rarely provide information on their spatial and temporal dependence, which are often relevant features for impacts. For example, the joint occurrence of heavy precipitation events in the same catchment, or in close succession, possibly in combination with wet soils[81], typically cause the most severe flooding events. To improve our confidence in the projection of extremes, model evaluation[82] needs to expand towards the evaluation of multivariate dependencies, requiring new metrics and tools that are subject to the availability of observational data[83]. If we evaluate and improve processes and variable combinations that are associated with extremes, model predictions of extremes can be improved. For instance, constraining a model ensemble by the occurrence rate of soil-moisture-limited climate regimes[84] improves the predictions of daily temperature extremes[85].

Tests that evaluate whether models display the correct multivariate dependence structure can also be used for multivariate bias correction[86,87]. This is highly important when (global) climate models are to be coupled with impact models[88], as impact models rely

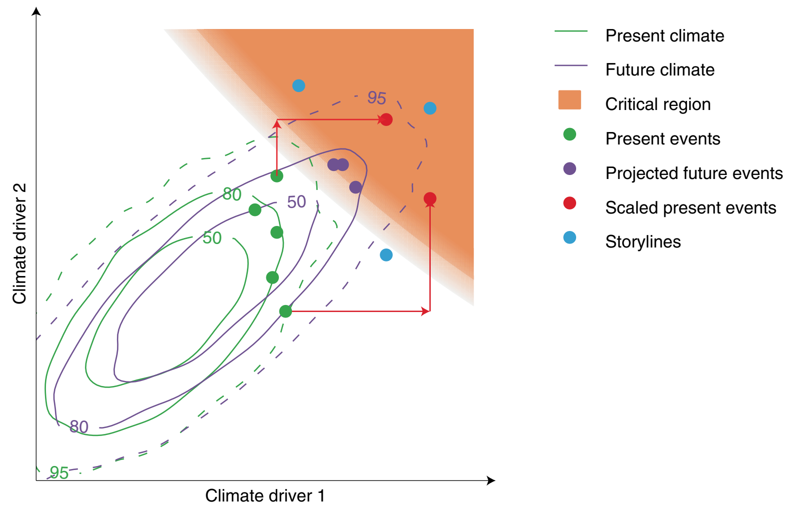

Fig. 3 | Illustration of different possibilities to simulate potentially critical events. The hypothetical present-day distribution of two climatic drivers and their potential future distribution. Continuous lines depict the 50th and 80th percentiles, dashed lines denote the 95th percentiles. The coloured points denote different possibilities to generate potentially critical events. The critical region is shown in orange with a blurred border to illustrate uncertainty in the estimation of its extent. The critical region can only be known if enough critical events have occurred (or can be simulated) to characterize it.

on unbiased model output for both the driving variables and their interdependencies[63]. Commonly used bias adjustment methods in impact modelling frameworks do not correct for the multivariate dependence structure[89] and often lead to undesired adjustments of the tails[90]. Multivariate bias correction approaches thus need to be designed to produce realistic tail behaviour. The bias adjustment procedures preferably take into account that observational data, as well as models, are likely to have shortcomings in the representation of the dependence structure. For instance, currently available observation-based climate data products may not provide an adequate constraint on the interannual correlation between temperature and precipitation in the warm season for large parts of the Southern Hemisphere due to limitations in the record length and quality of data[7].

Some events have such severe impacts that they can be referred to as 'game-changing events', which elicit 'crucial decisions'[50]. For example, a flood that causes loss of lives and property is likely to be followed by the construction of additional infrastructure, modification of planning regulations and many other features[91]. Therefore, experiencing an event often leads to improved resilience to similar future events, such that areas of vulnerability are more likely to be due to events or combinations of events that have yet to occur. Thus, a sophisticated planning procedure aimed at increasing resilience against adverse climatic extremes also needs to take into account consequences of events that have not yet occurred. For example, a hurricane like Harvey hitting Texas is a phenomenon that does not readily emerge from traditional analysis techniques using observational records of limited length, or coarse-resolution climate modelling archives with a limited ability to reproduce the relevant physical processes. Even statistical weather generator techniques need to be conditioned heavily to reproduce the unique configuration that characterized Hurricane Harvey.

To account for unprecedented events with potentially game-changing impacts, alternatives to traditional risk assessment are required. Storytelling techniques are ways to visualize conditions that are considered relevant but have no precedent in observational records[43]. The simulated events can either be constructed from past events and manipulated to be consistent with future (climate) conditions (for instance by rerunning a weather prediction model that captured an extreme precipitation condition but with elevated climate forcing[92]), or selected from a large set of synthetic event simulations from weather generators or climate model outputs (see Fig. 3 for an illustration). Moezzi and co-authors[39] discuss storytelling in climate change, emphasizing the intersection between nature, humanity and technology disciplines to create and analyse their applications. Storylines describe past or (hypothetical) future events and their impacts, as a means to illustrate climate change features without assigning a probability to them[43]. Storyline approaches extend traditional scaling approaches, in which projected future changes are added to climate conditions of the past (Fig. 3).

Storyline approaches cannot be regarded as stand-alone alternatives to formal statistics-based scenario constructions and analyses. A solid context of the conditions under which the events may take place must still be available in the form of mainstream climate change scenarios, human development, socio-economic trends and others, to support the decision process with respect to increasing resilience against these events. However, as a supplementary source of information it does contribute to an enhanced understanding of the dynamics of the system that may challenge societal actors. Analysis of compound events using storytelling techniques is very appropriate because of their rare and often unprecedented nature. In practice, the analysis of compound events using storytelling techniques relies on realistic modelling capacity to simulate relevant events or sample them from large enough observation- or model-based event archives. Constructing portfolios of relevant compound events has to be inspired by both the drivers and the impacts of the events, where multiple features jointly operate to generate a large impact.

Conclusions

Many major catastrophes bear the hallmark of being caused by compound events. While efforts to understand single drivers of extreme events will continue, a refocusing of activity towards compound events would help to bridge the gap between the climate science and impact modelling communities. We believe that this refocusing can be achieved via the following five recommendations:

- In scientific practice, it should be recognized that most major weather and climate-related catastrophes are caused by compound effects of multiple drivers. A systematic research programme focused on these systems is overdue and is necessary to improve risk management for vulnerable communities;

- Theoretical frameworks and supporting tools for risk assessment and attribution that explicitly account for compound events must be developed. A focus on compound events will draw attention on the targeted methodologies, tools and data that will enable better risk management of climate-related impacts;
- Bottom-up methodologies are needed to identify the combinations of climate drivers and hazards that collectively lead to changes in risk. This requires an increased emphasis on applying climate stress tests to systems to identify areas of vulnerability before failure occurs;
- Resolving compound events in climate projections will require a different analysis methodology that focuses on impacts rather than on drivers. This focus may reinforce the view that major improvements in global climate model resolution, improved downscaling techniques and innovation in computing and data management are required. However, this focus may also identify major gaps in our science that must be addressed before we can use climate models for robust projection of compound events;
- Understanding and modelling the changing nature of human activities (such as urbanization, infrastructure, anthropogenic emissions) and their interactions with compound events requires substantial attention[65]. Far stronger collaboration and synchronization across multiple fields of research will be necessary to improve our understanding of how compound events develop and impact vulnerable communities.

Adopting an impact-centric perspective[28,93] provides guidance for identifying the most relevant hazards and climatic drivers. Considering a hazard as a compound event and decomposing it into its contributing variables provides a pathway for a better understanding of the underlying physical processes and will guide future model development towards resolving the processes — and interaction between processes — that will lead to improved modelling and estimation of risk. Through the incorporation of dependencies into estimates of hazard likelihoods, we can improve short-term predictions as well as longer-term projections of hazards. Ultimately we may be able to build more resilient systems. The active consideration of compound events in the climate sciences brings a new analysis framework into climate research and complements conventional projections of climate extremes.

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Competing interests

The authors declare no competing interests.

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Correspondence should be addressed to J.Z.

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