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Climate change increases extreme rainfall and the chance of floods

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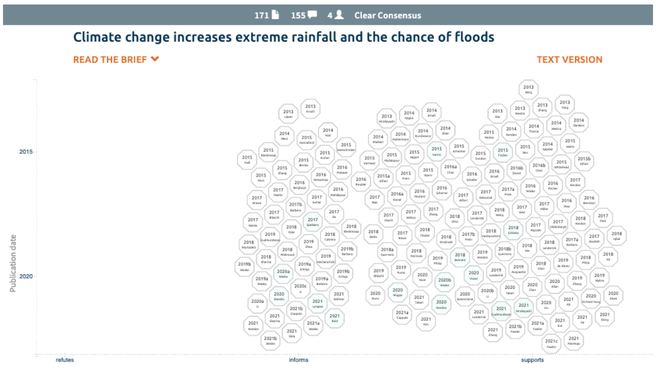
Approach. This ScienceBrief Review examines the links between climate change and extreme rainfall that can lead to severe flooding. It synthesises findings from more than 170 peer-reviewed scientific articles gathered using ScienceBrief. The Brief and evidence can be explored at: https://sciencebrief.org/topics/climate-change-science/extreme-rainfall-and-climate-change.

Summary. Climate change increases the frequency and intensity of extreme rainfall because a warmer atmosphere holds more water vapour that can rain out, sometimes over a short period. The movement of water vapour through the atmosphere, in storms, is also modified. Increases in extreme rainfall have been observed in many parts of the world. Extreme rainfall, in turn, can increase the chance of floods occurring and their magnitude in small and in urban catchments, severely impacting local populations and infrastructure. Extreme rainfall and associated flood hazards are projected to increase as global temperatures continue to rise.

Key points

The evidence shows clear consensus that climate change is causing an increase in the intensity of extreme rainfall. While economic losses from floods have risen due to socioeconomic and demographic factors (Hoeppe, 2016), observations suggest peak river flows (used as an indicator of potential floods) have decreased in most rural catchments (Wasko & Sharma, 2017) but increased in small and/or urban ones (Sharma et al., 2018). Future projections suggest that much of the world will experience enhanced rainfall extremes and risk of flooding with ongoing climate change (Arnell & Gosling, 2016; Alfieri et al., 2017; Tabari 2021). Efforts to limit warming to +1.5°C will help limit changes in extreme rainfall, whilst further societal adaptations will be needed to minimise the impact.

- Extreme rainfall intensifies with rising dew point temperature at a rate of around +6% to +7% per °C, in line with theoretical expectations from thermodynamics, known as Clausius-Clapeyron scaling (Ali et al., 2018, 2021).
- In many regions, including Australia, Europe, North America and Asia, extreme sub-daily rainfall intensifies with surface air temperature at greater than Clausius-Clapeyron scaling for localised regions, due to convective feedbacks from clouds and changes in atmospheric circulation resulting in increased moisture being drawn in to storms (Lenderink et al., 2017; 2021). When averaged over large regions, scaling is around Clausius-Clapeyron (Ali, 2021).



Snap shot of the Brief at the time of publication showing clear consensus among the evidence analysed. Click here to visit the Brief.

- Some extreme rainfall and storm events have been demonstrated to be somewhat more likely to occur due to climate change in examples from the UK, France, Louisiana, and southern South America.
- Observations of high river flows vary regionally but trends are decreasing in the majority of rural catchments and increasing in urban catchments, highlighting the complex interplay of processes that control flooding.
- In recent years, very high resolution climate models have brought much improved representations of extreme rainfall intensity (Prein et al., 2015; Kendon et al., 2017), which suggest extreme rainfall will become more intense with continued future warming (Kendon et al., 2014; 2017; 2019).
- Future increases in rainfall intensity, projected by theory and modelling, may result in clearer flooding trends, though much more extensive river flow observations will be required for detection, especially for rapid, flash floods (Fowler et al., 2021a).

Background. Extreme rainfall events result in significant societal impacts, including flooding and landslides, leading to major socioeconomic damages (Debortoli et al., 2017; Spekkers et al., 2017). Assessment in the IPCC special report on global warming of 1.5°C noted a likely increase in frequency, intensity and/or amount of extreme rainfall in several regions. However, predicting the response of future rainfall rates to climate change is less certain than predicting future temperature (Knutti and Sedlácek, 2013). Modelled rainfall variability across daily to decadal timescales is projected to increase, on average, and several regions, including in south and east Asia, northern Australia and Brazil, are projected to experience both drier or more frequent dry periods and wetter wet periods (Brown et al., 2017; Alves et al., 2020).

This review focuses on the response of extreme rainfall, representing the highest intensity portion of total rainfall, to climate change. Extreme rainfall is often defined by the 99th percentile, referring to the most intense 1% of rainfall, or alternatively the annual maxima, the highest total in a year, typically over 24 hours. It is possible for increases in extreme rainfall intensity to occur during a background reduction in total rainfall, if there is a reduction in low-medium intensity rainfall (Ban et al., 2015; Tabari, 2020).

Theory

It is well established that the frequency and intensity of extreme rainfall increases more strongly with global mean surface temperature than does mean rainfall (Berg et al., 2013; Myhre et al., 2019) as the latter is limited by evaporation, whilst changes in extremes are also affected by local in-storm processes. In simple terms, warmer air can hold more water vapour that can subsequently fall as rain. For each degree of warming, the air's capacity for atmospheric water vapour increases at about +6% to +7% per degree of warming, assuming other atmospheric conditions remain roughly constant, known as Clausius-Clapeyron scaling (Allan et al., 2014). A warming atmosphere with more moisture can therefore produce more intense rainfall events, with this scaling providing a first approximation (Fowler et al., 2021a). A wide range of other processes are also important in driving changes in extreme rainfall, including atmospheric circulation patterns, sea surface temperature and large-scale atmospheric circulation systems such as the El Niño-Southern Oscillation (ENSO), changes to land cover or land use, and atmospheric aerosol concentration.

Scaling rates around Clausius-Clapeyron have been observed between day-to-day temperature variability and daily rainfall extremes (Ali et al., 2018) but sub-daily extreme rainfall intensity can exceed Clausius-Clapeyron scaling, reaching as much as double (+10% to +14% per °C) (Lenderink et al., 2017; Park et al., 2017; Zhang et al., 2017; Ali et al., 2021). This relationship is not uniform, and intensities sometimes rise at a lower rate at higher temperatures (Chan et al., 2016a; Park et al., 2017; Zhang et al., 2017; Drobinski et al., 2018) and is constrained by moisture availability (Park et al., 2017; Prein et al., 2017a; Zhang et al., 2017), and can potentially vary due to large-scale atmospheric conditions (Blenkinsop et al., 2015; Magan et al., 2020) and seasonality (Fowler et al., 2021a). The enhanced scaling relationship for sub-daily extremes could relate to local factors like storm size (Fowler et al., 2021a), a combination of convective cloud feedbacks, and changes to large-scale atmospheric circulation (Lenderink et al., 2017; Fowler et al., 2021a; 2021b), whilst local-scale increases and large-scale decreases in the instability of the atmosphere could have confounding effects (Fowler et al., 2021a). The impact of moisture availability is particularly important as local circulation changes, due to convection, can draw moisture into storm centres. Dew point temperature, which relates closely to relative humidity, has therefore proved to be a more consistent metric for estimating the scaling of extreme rainfall than near-surface air temperature (Lenderink et al., 2017; Barbero et al., 2017a; Ali et al., 2018). This scaling is consistently around the Clausius-Clapeyron rate when averaged over most regions with higher scaling only observed at local scales (Ali et al., 2021). However, more consistent results with near-surface air temperature have been obtained using data that resolve within-day temperature variations and better reflect prevailing storm conditions (Schleiss, 2018; Visser et al., 2020). It is not yet clear whether future rainfall change with warming will be consistent with these rates although climate models are starting to provide such evidence (Lenderink et al., 2021).

Observations

Increases in daily extreme rainfall rates have been observed globally and on continental scales through the 20th and early 21st centuries concurrent with rising average surface temperature. Studies of daily precipitation overwhelmingly indicate that extremes have generally become more frequent and more intense globally over the past century (Westra et al., 2013; Donat et al., 2016a; Dunn et al., 2020; Dong et al., 2021; Sun et al., 2021) whilst more detailed studies have indicated similar results on continental scales (Dong et al., 2021; Sun et al., 2021) including over both dry and wet regions (Donat et al., 2016b). Continental scale increases in the frequency of daily extremes over Europe and the United States (Fischer & Knutti, 2016) and in their frequency and intensity over Australia (Guerreiro et al., 2018b) are consistent with theory. Increases in frequency of occurrence have been noted to be greatest for the most extreme events, as highlighted by the IPCC Third Assessment Report, whilst similar behaviour over large domains is also noted by Myhre et al. (2019). However, patterns of change vary on regional scales, the clearest increasing trends are for northern Europe and central Eurasia whilst there remains a lack of long data records over Africa, the Amazon region, and parts of southeast Asia (Donat et al., 2016a).

Lack of sufficiently long records in many areas has prevented robust statements on global changes in short-duration (e.g. hourly) rainfall extremes but increases have been detected in several regions including the United States and parts of Europe, southeast Asia, India and Australia (Fowler, 2021a). Increases in the frequency and intensity of hourly rainfall extremes have been found to exceed those of daily extremes in Australia (Guerreiro et al., 2018b). Results from high resolution climate models have corroborated the observed trends over the United States (Prein et al., 2017a).

Observations from a broad range of latitudes and environments have demonstrated an increase in daily extreme rainfall intensity of around +6% to +7% per degree of warming of surface air temperature, matching expectations in accordance with Clausius-Clapeyron scaling and climate model simulations (Westra et al., 2013; Fischer & Knutti, 2016; Scherre et al., 2016). Guerreiro et al. (2018b) detected observed continental-scale increases in hourly rainfall intensity and frequency for Australia at up to 2-3 times Clausius-Clapeyron scaling.

In most catchments, trends in high river flows are decreasing despite rising temperatures and increasing rainfall extremes (Wasko & Sharma, 2017; Wasko et al., 2019). Most studies of changes in floods have considered extremes in river flow data at daily timescales or longer and although they identify regional consistencies in the direction of trends (Do et al., 2017; Gudmundsson et al., 2019), globally more stations show significant decreasing than significant increasing trends. This is not consistent with the hypothesis that the increases in extreme rainfall (driven by increases in temperature) will drive increases in flood hazard globally. Some regional increases have been observed (Mallakpour & Villarini, 2015; Blöschl et al., 2019), for small catchments (Do et al., 2017) and urban catchments (Sharma et al., 2018) where the effects of moisture in the soil are small and floods are primarily driven by rainfall intensities (Ivancic & Shaw, 2015) that exceed drainage capacity. Possible increases have also been found for the rarest, most extreme floods (Wasko & Nathan, 2019). Whilst it is commonly assumed that increased global flood hazard may result from increases in extreme rainfall, flooding is influenced by a range of factors, summarised in Table 1, with soil moisture (evaporation) or snowmelt often the most influential (Gaál et al., 2015; Berghuijs et al., 2016; Sharma et al., 2018; Hettiarachchi et al., 2019; Wasko & Nathan, 2019). The lack of correspondence between these trends in high river flows and increased financial cost of floods points to concurrent increases in exposure and vulnerability to flood hazards (Do. et al., 2017). Furthermore, changes in the timing of high flows have been detected and may be associated with significant impacts (Blöschl et al., 2017; Wasko et al., 2020).

Flash flooding in urban areas has likely increased in recent decades, due to the expanding impermeable landscape increasing surface runoff, and increases in the intensity of short-duration extreme rainfall (Acquaotta et al., 2019). Flooding of small river catchments that respond rapidly to rainfall, and urban catchments where the soil moisture storage is less important, provides a more direct link between temperature, rainfall intensity and flooding. Therefore flooding in these catchments might be expected to rise due to extreme rainfall intensification as temperatures rise (Sharma et al., 2018). However, the role of extreme rainfall in these floods is difficult to isolate from the effects of urbanisation, which may itself lead to local increases in rainfall intensity (Li et al., 2020), and this is made more challenging by the sparsity of sub-daily river flow records (Fowler et al., 2021a). Inadequate drainage infrastructure that struggles to handle the increasing magnitude of extreme rainfall, may also contribute to urban flash flooding (Xiao et al., 2016).

Extreme rainfall attribution

Despite large natural variability, the influence of human activity on observed increases in extreme daily rainfall has been identified globally, on continental scales (Dong et al., 2021), and regionally in the case of North America (Kirchmeier-Young & Zhang, 2020). A study of Australian rainfall observations found increases to hourly extreme rainfall were in excess of that which could be explained by natural variations, such as the El Niño-Southern Oscillation (ENSO) or seasonality (Guerreiro et al., 2018b). Human influence was detected in the extremely wet winter of

Factors		**Selected References**
Natural	Catchment characteristics including elevation, terrain, vegetation, size	Do et al. (2017); Wasko & Sharma (2017); Fowler et al. (2021a)
	Soil moisture	Berghuijs et al. (2016); Sharma et al. (2018); Bennett et al., (2018); Wasko & Nathan (2019)
	Snowmelt	Gaál et al. (2015); Berghuijs et al. (2016)
	Humidity	Barbero et al. (2017a)
	Storm-surge	Thorne (2014)
	Large-scale atmospheric circulation	Mallakpour & Villarini (2016); Davolio et al. (2018); Reid et al. (2021)
	Event rarity or magnitude	Wasko & Sharma (2017); Sharma et al. (2018); Wasko & Nathan (2019)
Human	Urban infrastructure	Hannaford et al. (2015); Xiao et al. (2016); Miller & Hutchins (2017); Hettiarachchi et al. (2018)
	Demographic characteristics	Marengo et al. (2021)

Table 1. Factors influencing flooding, classified by whether they are natural or human derived. Selected references are indicative but not exhaustive.

2013/2014 in the UK (Vautard et al., 2016). A quantified increase in the likelihood of individual storms or flooding events, due to human influence, has been calculated for numerous examples including: three UK storms in December 2015, which are estimated to have collectively been +59% more likely (Otto et al., 2018). Flooding of the Seine and Loire rivers in central and northern France in May-June 2016, is estimated to have resulted from extreme rainfall that was +2.2 and +1.9 times more likely, respectively (Sjoukje et al., 2018). In south Louisiana, extreme rainfall in August 2016 was made more likely by a factor of +1.4 compared to 1900 (van der Wiel et al., 2017). In April–May 2017, extreme rainfall in the Uruguay River basin, Southern South America, was made more likely by a factor of almost five (de Abreu et al., 2019). Climate change attribution in extreme rainfall associated with hurricanes and tropical cyclones is discussed in a separate ScienceBrief Review of tropical cyclones.

Future projections

Relatively coarse-scale global climate models show future increases in daily rainfall extremes over most land regions with warming (Seneviratne & Hauser, 2020; Coppola et al., 2021a). Regional studies using global models and more detailed regional climate models show a similar picture (e.g. Ge et al, 2021, Coppola et al 2021b, Kim et al, 2021) although there remains uncertainty on the magnitude of change at regional scales. Regional climate model performance improvements project increased extreme rainfall over the La Plata basin in South America, the Congo basin in Africa, east North America, north east Europe, India and Indochina regions, while less detailed global models show weak or negligible trends (Coppola et al., 2021a).

In recent years, very high resolution climate models have brought much improved representations of extreme rainfall intensity (Prein et al., 2015; Kendon et al., 2017). Historically, climate models have not accurately captured extreme rainfall intensity, due to their resolution being too coarse to reproduce small-scale (1-10km^2) clouds and other processes that control rainfall (Kendon et al., 2017; Zhang et al., 2017). Convection-permitting models (CPMs) can produce regional-scale simulations at a resolution of ≤4km, enabling storm processes such as cloud convection and local feedbacks to be simulated within the model, rather than using parameterisation (inputting generalised values). They are also able to capture more detailed local surface features like mountains (Ban et al., 2015). CPMs have now been run over many regions (Fowler et al., 2021b) but are yet to be run globally, because of their high level of detail. Ground-breaking CPM experiments over the UK point to more intense hourly rainfall extremes with future warming (Kendon et al., 2014; Chan et al., 2018) and this advance in modelling is now incorporated in the national UK Climate Projections using multiple model simulations (Kendon et al., 2020). Elsewhere, CPMs also point to more intense storms with climate warming over Europe (Lenderink et al. 2019; Chan et al., 2020), the US (Prein et al., 2017a,b) and Africa (Kendon et al., 2019). Future understanding of potential changes in flood risk will also require an understanding of how the total volume of rainfall in a storm will change and CPMs offer the potential to be used alongside rainfall observations to understand how storm size and duration might change (Wasko et al., 2016; Prein et al., 2017b; Lochbihler et al., 2017). Despite their limitations, such as producing heavy rainfall that tends to be too intense, and difficulty in quantifying future uncertainties, the ability of these models to project future changes in extreme rainfall is a significant advance (Kendon et al., 2021) and is providing confidence in future projections of more intense sub-daily rainfall (Prein et al.,2015; Kendon et al., 2017).

Projected increases in extreme rainfall intensity drive an increase in flooding in small and/or urban catchments (Kendon et al., 2018), with flash flooding projected to increase in at least the U.K. (Miller & Hutchins, 2017), Egypt (Mahmoud et al., 2018), Indonesia (Muis et al., 2015), Brazil (Marengo et al., 2020), and China (Xiao et al., 2016). However, many other factors control flooding (see Table 1), and these may compensate for increases in extreme rainfall. If all factors remain constant, increased extreme rainfall would result in increased flooding; however, it is likely climate change also varies some of these other factors (Sharma et al., 2018).

Significant uncertainty remains when attempting to translate projected increases in extreme rainfall to an overall increase in flood hazard (Fowler et al., 2021a; Wasko, 2021a). There has been little research directly translating projected changes in extreme rainfall through hydrological models to estimate changes in flood frequency (Hirabayashi et al., 2021). Although future warming points to increases in rainfall intensities and the scaling relationship between temperature and the most extreme flows could inform some future changes in flooding (Wasko, 2021a), projections of these changes will also need to account for changes in other factors (see Table 1). Climate change may also alter the structure of storms so they become bigger (Prein et al., 2017b) or longer in duration (Chan et al., 2016), increasing the volume of rain falling over a location. Further research is needed to fully understand how such changes might affect flooding and the need for societies to adapt.

This ScienceBrief Review is consistent with the IPCC Special Report on 1.5 degrees (2018) Chapter 3 and Special Report on Climate Change and Land (2019) Chapter 4, both of which noted that human-induced global warming has already caused observed increases in the frequency, intensity and/or amount of extreme rainfall in several regions. Furthermore, this review is consistent with the findings reported in the discussion meeting issue of the Royal Society ‘Intensification of short-duration rainfall extremes and implications for flash flood risks’ (2021).

The full Brief and references can be explored on ScienceBrief with the following link: https://sciencebrief.org/topics/climate-change-science/extreme-rainfall-and-climate-change.

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