Anthropogenic intensification of short-duration rainfall extremes

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Abstract | Short-duration (1–3 h) rainfall extremes can cause serious damage to societies through rapidly developing (flash) flooding and are determined by complex, multifaceted processes that are altering as Earth's climate warms. In this Review, we examine evidence from observational, theoretical and modelling studies for the intensification of these rainfall extremes, the drivers and the impact on flash flooding. Both short-duration and long-duration (>1 day) rainfall extremes are intensifying with warming at a rate consistent with the increase in atmospheric moisture (~7% K^{-1}), while in some regions, increases in short-duration extreme rainfall intensities are stronger than expected from moisture increases alone. These stronger local increases are related to feedbacks in convective clouds, but their exact role is uncertain because of the very small scales involved. Future extreme rainfall intensification is also modulated by changes to temperature stratification and large-scale atmospheric circulation. The latter remains a major source of uncertainty. Intensification of short-duration extremes has likely increased the incidence of flash flooding at local scales, and this can further compound with an increase in storm spatial footprint to considerably increase total event rainfall. These findings call for urgent climate change adaptation measures to manage increasing flood risks.

Intensification of the hydrological cycle is one of the known effects of a warming climate, with rainfall extremes having increased since 1950 (REFS[1–3]). However, uncertainty remains in understanding changes to rainfall extremes, particularly for short-duration (1–3 h), relatively small-scale (tens of kilometres or less) convective events. Changes to rainfall extremes have been assessed on the basis of the frequency of events above a threshold or the intensity at a given frequency, often a percentile, such as the 99th or 99.9th (or the return period). Although changes in frequency and intensity have the same sign, the amplitude of the change differs depending on the shape of the rainfall distribution. Usually, percentage changes in the frequency of the most extreme events exceed those in intensity — a property that is tied to the distribution of rainfall extremes[4].

Central to understanding increases in extreme rainfall intensities due to warming is the Clausius–Clapeyron (CC) relation. This relation governs the saturation specific humidity of the atmosphere as a function of temperature, increasing at a rate of ~7% per degree warming (K^{-1}) near the Earth's surface. Given that other atmospheric conditions, such as relative humidity, remain approximately constant with warming across most of the land surface, the absolute (specific) humidity of the air also increases at roughly the same rate[5,6]. As rainfall extremes are limited by the amount of atmospheric moisture available, changes to rainfall intensities are, to a first approximation, expected to scale with the CC relation[7].

Several studies have confirmed an approximately CC rate of increase in observations and projections of daily extreme rainfall[1,2,8–10] when averaged globally, whereas locally, substantial deviation from these scalings can be explained by changes in local meteorology. The relation between extreme daily rainfall intensities and short-term (day-to-day) variability in temperature — the 'apparent scaling' — also approximately follows the CC rate at most locations worldwide[11]. However, for sub-daily intensities, some studies suggest an increased sensitivity to warming, with the occurrence of super-CC scaling (apparent scaling rates >7% K^{-1}) in some locations[12–16]. Physical processes, particularly related to convective clouds, can plausibly explain super-CC apparent scaling. Suggested mechanisms that could lead to this enhanced sensitivity are dynamical feedbacks in cloud-core updrafts[7,17,18], cloud–cloud

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Key points

- Heavy rainfall extremes are intensifying with warming at a rate generally consistent with the increase in atmospheric moisture, for accumulation periods from hours to days.
- In some regions, high-resolution modelling, observed trends and observed temperature dependencies indicate stronger increases in short-duration, sub-daily, extreme rainfall intensities, up to twice what would be expected from atmospheric moisture increases alone.
- Stronger local increases in short-duration extreme rainfall intensities are related to convective cloud feedbacks, but their relevance to climate change is uncertain, owing to modulation by changes to temperature stratification and large-scale atmospheric circulation.
- It is unclear whether storm size will increase or decrease with warming; however, increases in rainfall intensity and the spatial footprint of a storm can compound to substantially increase the total rainfall during an event.
- Evidence is emerging that sub-daily rainfall intensification is related to an intensification of flash flooding, at least locally. This intensification will have serious implications for flash flooding globally and requires urgent climate change adaptation measures.

interactions driven by cold pools[19] and quasi-geostrophic large-scale vertical uplifting[18,20]. However, it is uncertain whether this observed super-CC scaling will translate into a similar climate change sensitivity or 'climate scaling'.

Changes to sub-daily rainfall extremes have been examined in multiple studies, ranging from convection-permitting modelling[21–24] and idealized model experiments[18] to assessments of observations[1,25]. An effort to update the state of knowledge has been coordinated through the INTENSE (INTElligent use of climate models for adaptatioN to non-Stationary hydrological Extremes) crosscut[26] of the GEWEX (Global Energy and Water Exchanges) Hydroclimatology Panel. INTENSE has led a unique and very-large-scale data-collection effort for sub-daily precipitation across multiple continents (collated in the Global Sub-Daily Rainfall (GSDR) data set[27]; FIG. 1), providing new insight into the global climatology of sub-daily precipitation extremes from gauge data[28]. Alongside this advance has been the development of new satellite retrieval methods for precipitation and regional-scale radar data sets. Together, these data sets have been used to quantify the effects of changes in temperature and humidity on precipitation extremes at different timescales, links between the frequency and intensity of heavy rainfall and large-scale circulation variability[29], and local changes to the spatial structure of intense storms[30]. However, despite this enhanced understanding from observations of the present-day climate, the degree to which these observed relationships will hold in a warming climate is still unclear.

The development of very-high-resolution convection-permitting model (CPM) simulations has enabled sub-daily, and even sub-hourly, precipitation extremes to be represented over continental-scale areas on (multi)decadal timescales[21,24,31–33] (the continental-scale domains available at a horizontal grid spacing of <5 km are shown in FIG. 1). CPMs explicitly resolve cloud dynamical processes, providing large improvements over coarser-resolution climate models with parameterized deep convection in the simulation of sub-daily precipitation, including intensity–frequency–duration characteristics[31,34–36], orographically enhanced extreme precipitation[35,37–39] and scaling relations[40]. CPM simulations use two main approaches. The first is pseudo-global warming[41–43], whereby a storm's environment is perturbed by mean climate change signals typically derived from global climate models. Pseudo-global warming is used to show how the characteristics of an extreme event (for example, a tropical cyclone) would change if it had occurred in a past (cooler and drier) or future (warmer and wetter) climate, or to create time-dependent lateral boundary conditions for downscaling with regional climate models[23,44,45]. Second, full downscaling of coarser-resolution climate model simulations is used to provide more realistic characteristics of sub-daily rainfall[46] for ensembles of events or full climate-scale runs, with the CPM simulating mesoscale processes that are unresolved in the driving climate model.

The CC rate of increase in extreme rainfall intensities implied across modelling and observations has obvious implications for the impact of these events, while super-CC climate scaling would have an even greater effect[47]. Short-duration rainfall extremes are particularly hazardous and are responsible for fatalities through flash floods and landslides that occur with little warning[48,49], as well as pollution incidents from combined sewerage networks[50]. Cities are particularly vulnerable to floods generated by heavy short-duration rainfall because their drainage infrastructure systems were built during the past centuries with a capacity based on historically lower rainfall intensities and because of the increase in impermeable surfaces; this vulnerability necessitates

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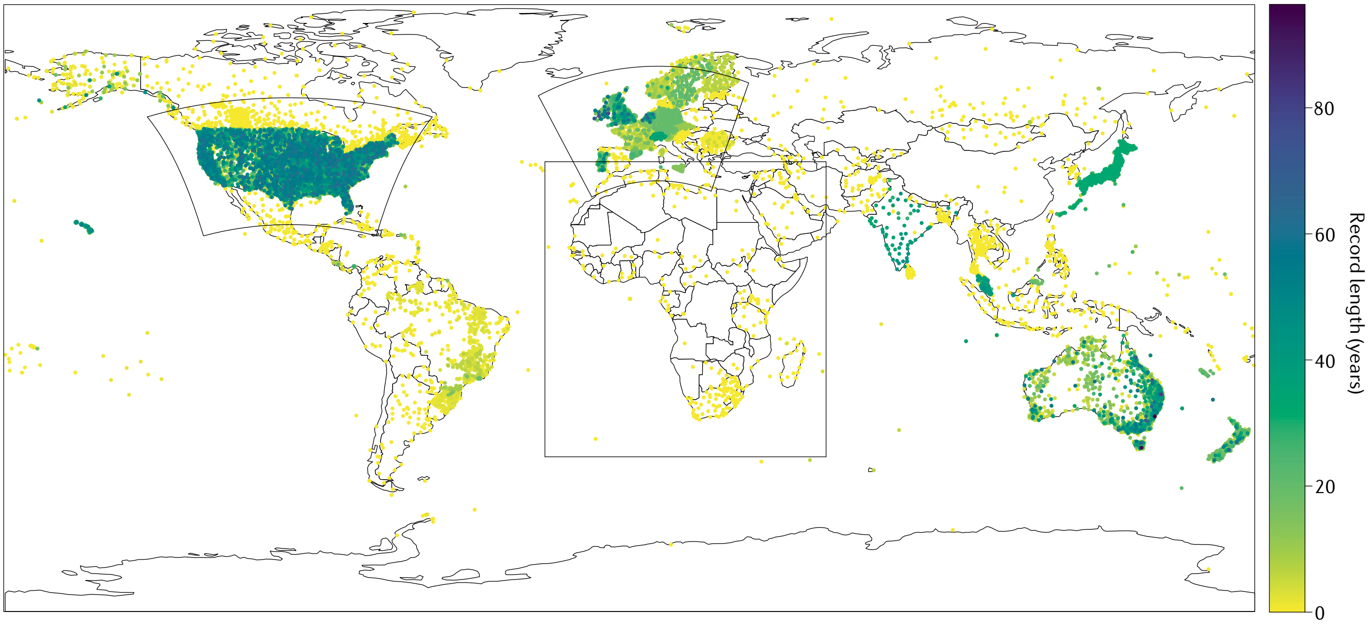

Fig. 1 | **The Global Sub-Daily Rainfall data set.** The Global Sub-Daily Rainfall data set comprises observed sub-daily precipitation data from across the globe[27]. The plot shows record lengths (that is, the time between the initial and the last recorded values) of hourly gauges remaining in this data set after quality control (coloured dots indicate gauge locations and record length) overlain by current continental-scale convection-permitting model domains at a horizontal grid spacing of <5 km (enclosed by black lines).

urgent adaptation measures. Improved understanding of the intensification of extreme (particularly short-duration) rainfall is crucial for effective climate adaptation, with important implications for broader science and engineering communities in managing the water environment.

In this Review, we synthesize the literature relating to the intensification of short-duration rainfall extremes through a process-based lens, using observed trends and temperature-scaling studies together with insight from high-resolution climate models to examine the changing characteristics of sub-daily rainfall extremes with warming and the drivers of these changes. In particular, we concentrate on bringing observational and model understanding together to describe the mechanisms of change, which has not been possible previously[8]. On the basis of this combined understanding, we propose a conceptual framework for understanding the intensification of short-duration rainfall extremes and assessing the implications for flood risks. Finally, we comment on the gaps in current knowledge and how these might be addressed.

Temperature scaling of extreme rainfall

As extreme rainfall changes appear to follow the increase in temperature and associated atmospheric water content, much research has concentrated on estimating scaling relations between extreme rainfall intensities and temperature from observed short-term climate variability — apparent scaling[51] — which might then be used as evidence to help understand how extreme rainfall will respond in a changing climate — climate scaling. However, the wide variety of methodological approaches[12,52–55], temperature measurements and rates (maximum, mean or interval ahead of rainfall) used complicate the interpretation of scaling results.

Daily extremes mainly show apparent CC scaling[2,3], but super-CC scaling (>7% K^{-1}) is observed in some locations (for example, Australia[6,56], the Netherlands[12,30,52] and Hong Kong[13]) for extreme hourly or shorter accumulations. For example, the apparent scaling relationships for the Netherlands (FIG. 2) show CC rates for daily extremes gradually changing to a regular 2CC (~14% per degree) rate for 10-min extremes. Apparent scaling strongly depends on the temperature measurements used, as well as on the portion of the temperature range analysed. Near-surface air temperature commonly produces CC or super-CC rates for hourly rainfall at low to moderate temperatures (10–20 °C), but negative rates (FIG. 3a) at moderate to high temperatures (>20–25 °C)[8,57–59]. Negative apparent scaling at high near-surface air temperatures is (partly) explained by the drier conditions necessary to generate the highest temperatures and the limited moisture availability on warm days[12,14,16,60,61], with high-pressure situations characterized by high temperatures and low (relative) humidity[40,62]. Including moisture in the assessment[61], through the use of dew-point temperature[60] (FIG. 3a), increases the consistency in apparent scaling across regions and temperature regimes, with dependencies close to CC or above, even in the tropics[11,13,14,63,64].

The use of apparent temperature scaling to project change to extreme precipitation with future warming is complex[51,65]. In order to serve as a useful predictor, the 'temperature'-scaling variable needs to be physically (and statistically) tied to rainfall extremes; using dew-point temperature as a measure of humidity, this condition is well fulfilled, owing to the central role of

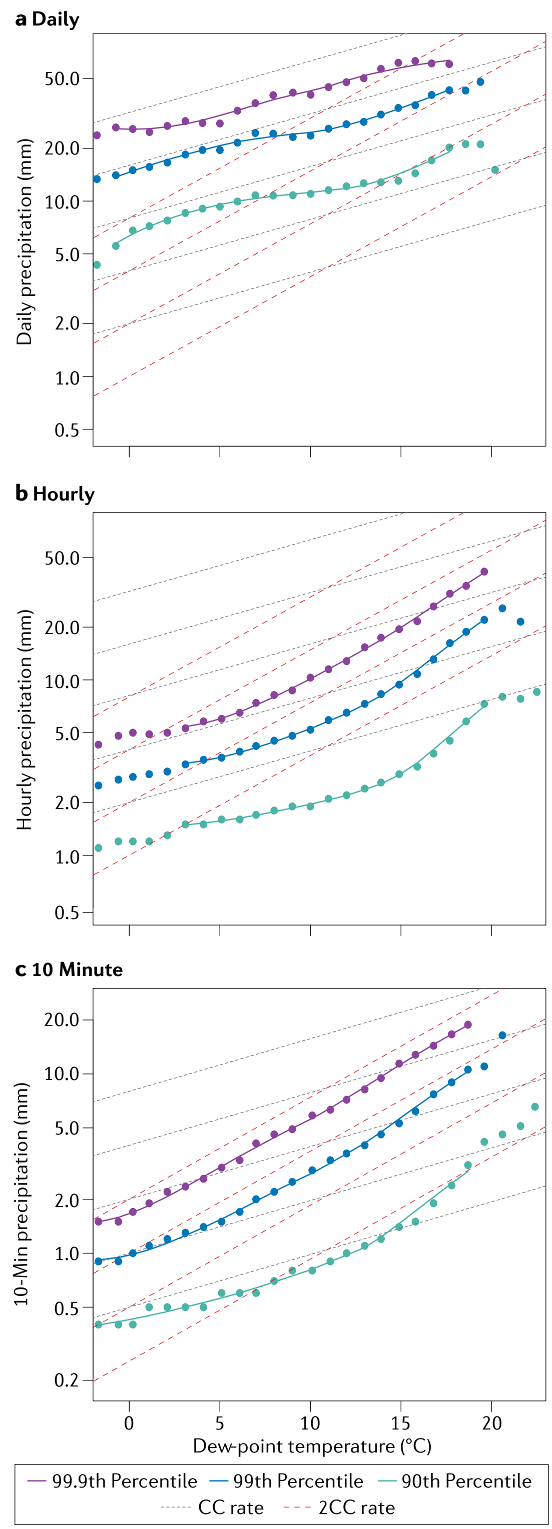

Fig. 2 | **Temperature scaling of rainfall intensities.** Apparent scaling of rainfall intensities with dew-point temperature at daily (panel **a**), hourly (panel **b**) and 10-min (panel **c**) resolution for the Netherlands, showing the 99.9th, 99th and 90th percentiles. Note that panel **c** has a different *y*-axis scale to panels **a** and **b**. The figures show the gradual change in apparent scaling rates from the Clausius–Clapeyron (CC) rate for daily precipitation to twice the CC rate (2CC) for 10-min rainfall extremes. Data from the Royal Netherlands Meteorological Institute (KNMI).

humidity in explaining the future intensification of rainfall extremes, resulting in consistent, positive apparent scaling (FIG. 2b,c). However, other properties of the atmospheric environment, such as atmospheric stability, relative humidity and large-scale circulation, are also required to co-vary similarly between day-to-day variations and long-term climate change for apparent scaling to translate to climate scaling[18]. Yet, in general, this may not be the case, although these effects may be less important for the most extreme events[66]. The balance between the influence of the scaling variable (surface humidity) versus that of the co-varying factors determines the usefulness of the scaling approach in explaining future, as well as past, changes, and likely depends on the region and season studied. Although promising outcomes have been reported[13,66,67], substantial discrepancies between apparent scaling and climate scaling have also been found[22,51,65,68].

Understanding the processes behind super-CC apparent scaling may allow the exclusion of systematic dependencies not relevant for climate scaling. For example, apparent scaling may reflect changes in meteorological regimes (such as a change from stratiform to convective rain types) with temperature[15,69] (FIG. 3b) or the mixing of large-scale and local forcing, particularly if large-scale flow conditions vary substantially between seasons[65,70]. The reversal of causal relations, whereby intense rainfall is itself the cause of temperature variations[51,60,61,71], may also influence apparent scaling. Despite these complications, temperature scaling can perhaps be expected to be similar for short-term variability and future (and past[13]) warming when sampling consistent meteorological regimes and by considering the influence of moisture and latent heat release[17,67]. However, changes to temperature stratification in the atmosphere and to large-scale (or even mesoscale) circulation variability[72,73] can also strongly affect extreme precipitation intensities but are not strongly connected to apparent temperature scaling.

Changes in sub-daily rainfall extremes

Changes to extreme rainfall intensity. A growing number of observational analyses point to increases in the frequency and/or intensity of sub-daily (primarily hourly) rainfall extremes in, for example, Australia[1], parts of China[74], Southeast Asia[75], Europe[76,77] and North America[78]. FIGURE 4 updates[8,79] and summarizes existing analyses of change from rain-gauge observations. The understanding of changes across large areas of the globe has been inhibited by a lack of data or lack of access to it, and, even when data exist, the nature and extent of quality-control checks on sub-daily rainfall data is not always apparent. Furthermore, a notable minority of studies identified in FIG. 4 consider only local-scale changes[80] from a small selection of gauges and, thus, may not adequately represent regional-scale changes. Results published to date are also not directly comparable with each other, owing to the application of different methodologies (for example, linear trends, extreme value theory), different metrics (for example, percentile-based, peaks-over-threshold, return periods) and different periods of analysis (for example, length of records, annual or

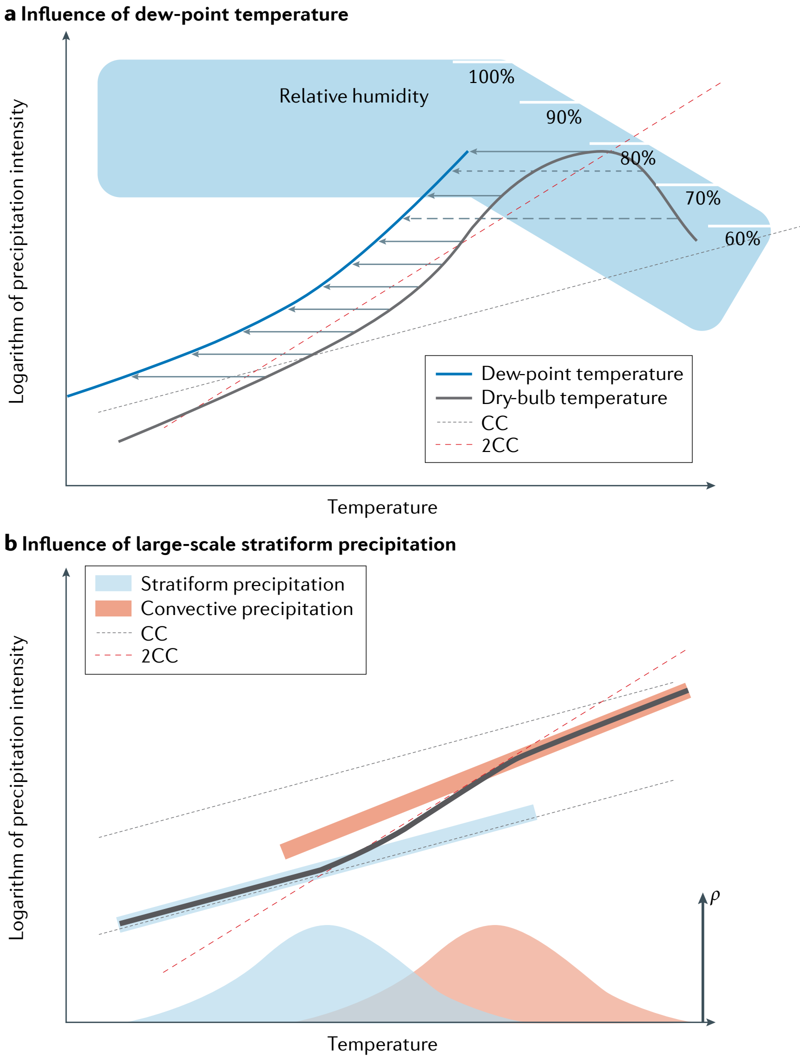

Fig. 3 | **Influence of accounting for humidity effects and rain types on the apparent scaling of high-percentile extreme rainfall. a** | Plot showing the effect of using dew-point temperature instead of dry-bulb (near-surface) air temperature on the apparent scaling of rainfall intensities. When relative humidity is declining at higher temperatures, the dew-point temperature decreases more strongly relative to the dry-bulb temperature, indicated by the grey (solid and dashed) lines, such that the hook shape seen in the dry-bulb curve is reduced or disappears. **b** | Rainfall intensity of large-scale stratiform precipitation distributed across a lower temperature range and convective precipitation across a higher temperature range, illustrating the differences in the intensity and apparent scaling (Clausius–Clapeyron (CC) and super-CC, respectively). Probability density functions (where ρ is the probability density) of the occurrence of each rainfall type are also shown as shaded surfaces. The combined apparent scaling (black solid line) becomes much steeper in the transition between the two distributions. 2CC, twice the CC rate.

seasonal). In some instances, relatively short periods of observations are used, which means that results may be sensitive to natural variability, rather than representative of long-term change[81]. The predominantly positive trends over the USA, Europe and Australia are consistent with the earlier initial review[8]; however, the previously identified positive regional trends indicated over South Africa are no longer robust across studies. A pattern of regionally varying change remains over China, although there is now evidence of increases over most of eastern China and decreases in the north. Several of the more recent studies also point to increases over Southeast Asia, but across the UK, the Republic of Ireland and Canada, despite multiple studies, no conclusive signal has emerged.

Linear-trend techniques remain the most common method of analysis (typically through application of a Mann–Kendall test) but are not necessarily appropriate for extreme precipitation, which is unlikely to show a linear response, even to strong forcing[82,83]. Furthermore, even when trends are examined across regional and national scales, few studies consider the field significance of any observed changes (see REF.[78] for an example of field significance testing). Thus, identifying the most appropriate methodologies for robust detection of rainfall change is a considerable issue. Although many observation-based change-detection studies identify and discuss warming as a potential mechanism for increased event frequency and/or intensity, few test this hypothesis or consider observed changes in the context of other potential drivers[81]. FIGURE 4, therefore, identifies studies in which sub-daily rainfall trends and/or changes are analysed in the context of observed temperature change or temperature scaling[13]; large-scale circulation and modes of variability[81]; or the potential influence of urbanization, through increases in anthropogenic aerosols[84] or the urban heat island effect[85], which is emerging as an interesting research area.

In some studies, intensification has been shown to exceed thermodynamic expectations. For example, peak intensities of extreme hourly rainfall are intensifying more rapidly than would be expected with global mean warming in Australia[1], at up to three times the CC rate. Although land is warming faster than the global mean, allowing faster rises in saturation specific humidity, this effect is not expected to enhance moisture increases over land, as the ultimate source of moisture is primarily the oceans, which are warming closer to the global mean rate. Other studies have corroborated this super-CC intensification[18,25,86], albeit with potentially low statistical certainty owing to short record lengths[87]. There is also evidence, mainly in tropical locations, for stronger precipitation systems and increases in peak intensities in urban areas with warming[88,89]; this intensification of hourly extreme precipitation tends to occur downwind of urban areas in mid-latitude locations, such as the US Midwest[90].

Results from CPMs corroborate these observed trends. Most CPM studies project higher intensification of sub-daily rainfall extremes than convection-parameterized models, with intensification almost always at or above the CC scaling rate[21–24,91–95]. Mesoscale models also find super-CC scaling of future intensities[67]. Furthermore, there is increasing evidence from CPMs that the peak intensities and frequencies of very rare, high-impact rainfall extremes will increase at a faster rate with warming[23,66,96]. At the same time, moderate and light rainfall hours are projected to decrease in frequency[97], resulting in future climates that are more favourable for both droughts and floods concurrently[22,24,98,99]. This relation is physically understandable, as global precipitation is constrained by the global energy budget to increase more slowly than extreme precipitation, thereby requiring sub-CC or even

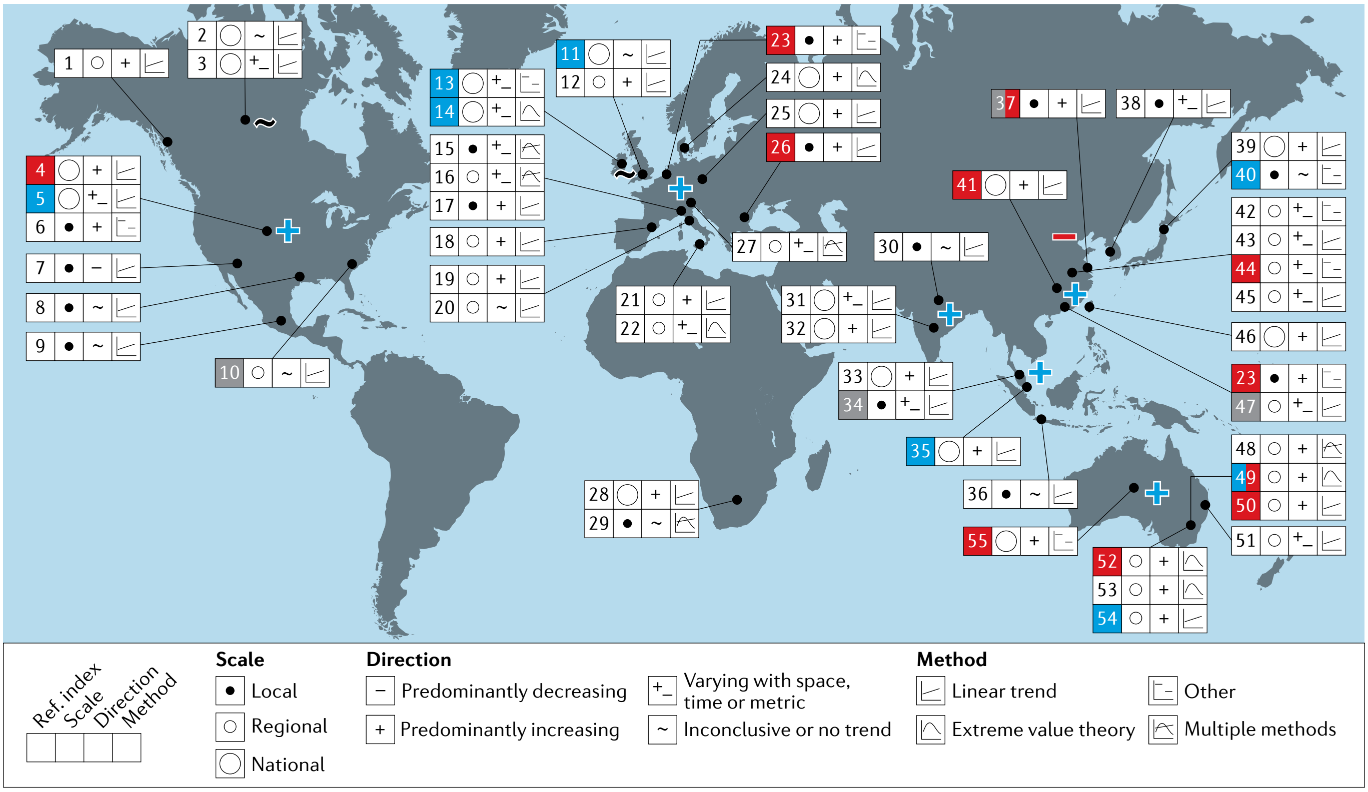

Fig. 4 | **Summary of existing knowledge of observed changes in the frequency and/or intensity of sub-daily rainfall extremes.** For each study, the spatial scale, the predominant direction of change and the methodology used are indicated. The direction of change includes analyses of different seasons, periods of analysis and metrics of extremes. The large symbols on the map indicate areas where a predominant direction of change is evident from a national-scale study or a majority of regional studies. The reference indices correspond to the citations provided in Supplementary Table 1 and the associated references in the Supplementary Information. The reference indices are colour coded to indicate whether results are analysed in the context of various drivers: temperature or temperature (Clausius–Clapeyron) scaling (red), large-scale circulation (blue) or urbanization (grey).

decreases in precipitation away from the wet regimes[100]. An observational study[56] also found more intense peak rainfall at the expense of total rainfall at higher temperatures in Australia, regardless of the climatic region and season.

Pseudo-global warming simulations have shown that extreme rainfall from tropical cyclones is already higher than during pre-industrial conditions and will likely continue to intensify under future warming at rates that are potentially higher than CC scaling[94,101–105]. Similar results have been found for flood-producing mesoscale convective systems[106–108] (MCSs) in the USA, idealized squall line simulations[109] and extreme rainfall in the Netherlands[110], which exhibit super-CC increases. These large increases have been partly related to more vigorous updrafts, but assessing uncertainties in CPM simulations remains challenging.

Differences in statistical approaches (for example, using conditional percentiles[55]) account for at least part of the spread in projections of future intensification from different modelling studies, but the region and dominant precipitation type (for example, convective versus orographic) also likely have an important role. Despite these differences, the signal of extreme rainfall intensification is robust across different climate types, latitudes and CPM structures[111]. CPM simulations indicate that sub-daily rainfall extremes are likely to intensify in regions and seasons where moisture supply is not limited[23,112]. However, modelling evidence does not support a fixed temperature threshold above which precipitation is limited by moisture availability[4,23].

Changes to storm structures. Other characteristics of extreme storms, besides rainfall intensity, are equally important for flooding but have not been studied extensively so far. Observational studies indicate that, for higher temperatures, precipitation events increase their peak intensity and become smaller in size in Australia[113] and Germany[114], but increase their peak intensity and become larger in the Netherlands[30]. This increase in storm size with climate warming is also shown in CPM pseudo-warming experiments for the USA[98]. For the UK, CPM simulations show peak intensity increases and storms becoming longer in duration with warming[32], although spatial aspects of storms were not examined. However, it should be noted that the duration at a given location is related to the spatial size of the storm multiplied by its propagation speed.

Studies focusing on MCSs in North America have shown that CPMs can capture MCS size, movement speed and evolution[106,115]. MCSs are the main cause of extreme precipitation in the eastern USA[116]. Hourly rainfall volumes from extreme MCSs might increase at much faster rates than CC, owing to a combination of close-to-CC increases in hourly peak rainfall rates and a spread of the heavy rainfall area[98]. This increase in peak intensities and spatial footprint of storms in a warming climate might result in even higher increases in total 'event' rainfall[98,101]. Increased moisture advection into future MCSs and changes in the cloud microphysics are possible causes of the rapid increase in precipitation volume, but further work is needed to understand the robustness of these results. The larger amplitude of the diurnal cycle of surface temperature, not just its mean or maximum, might also help MCSs to develop[117].

Disentangling drivers of change

The rate of intensification of rainfall extremes under climate change depends on various processes that range from the microscale to the synoptic scale and planetary scale. Recent observational and CPM studies have enhanced understanding of how these processes interact and how they might affect future extreme rainfall. Thermodynamic changes on their own — considering only direct humidity effects — result in an intensification of sub-daily rainfall extremes that is close to or slightly below CC scaling[23,101,107]. However, enhancing or damping this increase are several dynamical changes at small and large scales[72]. Idealized model experiments[17,18] and CPMs in pseudo-global warming experiments[67,109,110] indicate that feedbacks through enhanced latent heating with warming can lead to a super-CC response[17,118,119] for short-duration rainfall extremes. However, this response also depends strongly on stability changes of the atmosphere[44,120], with closer-to-CC dependencies and no evidence for dynamical invigoration of precipitation extremes when atmospheric stability changes follow a moist adiabatic lapse rate[17,121,122]. Storm intensification at the cloud scale combined with stability increases at larger timescales and spatial scales thus suggest that extreme rainfall responses to warming are time and space dependent[123]. We, therefore, split explanation of process interactions into three parts, according to the spatial scale. FIGURE 5 summarizes new understanding of the feedback processes affecting rainfall extremes and the key findings, mainly from model projections.

Cloud-scale dynamics and microphysics. Atmospheric stability (vertical lapse rate) has a key role in how convective systems respond to climate change. Intensity increases of mid-latitude convective storms are strongly related to increases in the convective available potential energy (CAPE) in both CPMs[124–126] and observations[28]. Climate models[127] and radiative–convective equilibrium modelling experiments[128–130] project that CAPE will increase thermodynamically with warming, implying notable increases in the future frequency of the occurrence of environments conducive to intense thunderstorms[131] in the mid-latitudes. This CAPE increase suggests that the thermal stratification of the

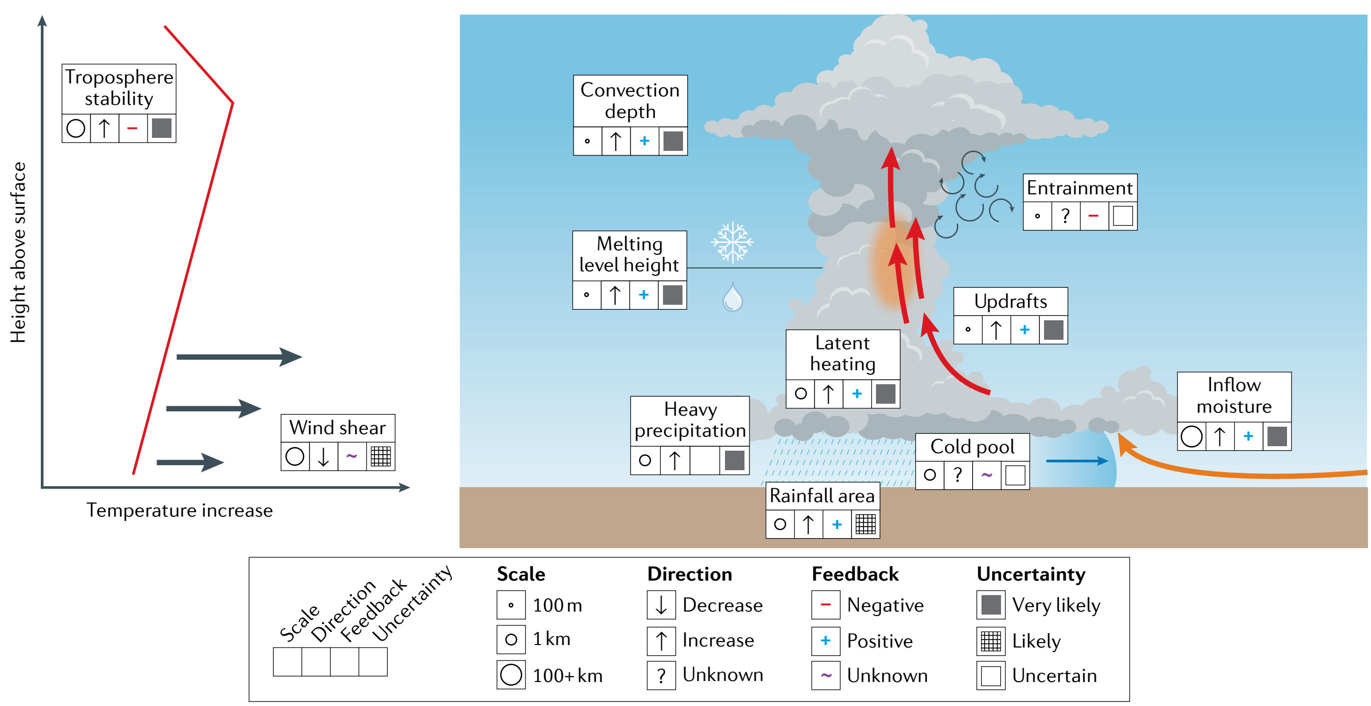

Fig. 5 | **Climate change-induced changes in extreme convective sub-daily precipitation processes.** Summary of the feedback processes affecting convective rainfall extremes. The plus and minus symbols indicate a positive or negative feedback, respectively, on extreme precipitation intensity. The order of the characteristic spatial scale is provided for each process, as well as the level of uncertainty: uncertain changes (little consensus, lack of research, missing first-order principle understanding), likely changes (some consensus, increasing amount of literature, based on first-order principles) and very likely changes (consensus established, changes have been detected in observational records). The feedback processes include stabilization of the troposphere owing to a reduced temperature lapse rate, weakening of wind shear[150,151], a higher melting level[96,140,145], deeper convection[96,171,172], increased latent heating[17,107,108], increased rainfall area[1,2,7,12,96], increased heavy precipitation, stronger updrafts[96,97,141], increased inflow of moisture[7,96], cold-pool changes[19,117,223] and entrainment changes[138,145,146].

atmosphere will deviate from a moist adiabatic lapse rate and is particularly significant at high temperatures[128]. Increased CAPE, reflecting greater buoyancy in convective clouds as a result of enhanced latent heating, could then lead to super-CC behaviour[17,118,119]; yet, evidence for stronger updrafts is still limited. Even when warming causes increases in CAPE and vertical velocities, precipitation extremes may not intensify at a super-CC rate; this is because the vertical profile of motion matters, with changes in vertical velocity at low altitudes more important than changes at greater heights, as most of the moisture is at low levels[121,132,133]. In the tropics, where the vertical profile is close to a moist adiabat, CAPE might not be the strongest predictor, and organized convection has a crucial role in generating extreme precipitation[134]. Urban heat islands also affect extreme rainfall intensities, destabilizing the atmosphere and increasing vertical velocities and, therefore, moisture convergence, which sustains a local circulation initiated by the relative warmth of the urban area[135].

Despite increases in local-scale instability, thermodynamic increases in stability and reduced relative humidity[136] at continental scales will increase convective inhibition and prevent low-level buoyant air from ascending[99,137]. Cloud mixing could lead to smaller changes in buoyancy than CAPE changes would imply[128]. This effect will suppress weak and moderately intense convection from forming, owing to more effective entrainment reducing buoyancy in a warmer atmosphere[128], although the intensity of strong convection[24] may be enhanced, owing to stronger organization and a smaller effective entrainment. However, changes to entrainment under future warming and its effect on extreme precipitation are not well understood. CPM simulations underestimate cloud entrainment processes[138], resulting in updrafts that are too strong and precipitation intensities that are too high at the surface[139,140]. Idealized modelling results show that resolving entrainment demands large-eddy simulation[141] (with grid spacings of ~200 m). Realistically simulating entrainment processes is crucial to preserve realistic cloud properties and for simulating rainfall, even more so under conditions of decreasing relative humidity in a future climate[142].

Climate change will also affect cloud microphysics[143]. The more intense convection in future climates will result in a higher ratio of graupel and hail in the cloud[46,98,144], which can enhance downdraft velocities and precipitation rates. As hail and graupel will develop at higher altitudes but encounter enhanced melting before reaching the surface owing to an increase in the tropospheric melting level height[46,98], the liquid water content in future clouds will likely increase, resulting in a more active warm rain process and enhanced surface precipitation[45]. However, uncertainties remain: the process might be different for different regions (for example, the tropics) and probably also depends on the model microphysics scheme. Modelling evidence has shown that increases in convective rainfall extremes are partly controlled by microphysical processes that involve droplet and ice fall speeds; super-CC scaling could, hence, be the result of differences in ice and droplet fall speeds[143,145]. Changes in precipitation efficiency are also closely related to changes in cloud microphysics, changes in entrainment and convection dynamics. For a long record of observations in the tropics, precipitation efficiency at convective scales increased with precipitation rate and mid-tropospheric humidity, and decreased with increasing CAPE and surface temperature[146]. However, these efficiency differences do not directly translate to changes in precipitation intensity, owing to compensating changes in cloud updraft velocities[146]. Climate change effects of precipitation efficiency are uncertain, with changes in efficiency found at different temperatures[145] and some evidence of increases in efficiency with warming in small domains, although this is complicated by changes to convective organization[147].

Cold pools appear to be a crucial part of the dynamics of convective clouds and how they respond to warming[148]. Changes in downdrafts are related to changes in cold-pool strength[149], with wider and deeper clouds developing as a result of stronger cold-pool dynamics[19,150]. Cold pools also likely mediate the 'communication' between convective clouds and, thereby, the initiation of new convective cells through interaction by mechanical or thermodynamic lifting at locations of gust front collisions. There may be an explicit link between convective organization and the emergence of extreme convective events over scales beyond that of a single convective cloud through cold pools[151]. Climate change impacts on cold-pool characteristics are highly uncertain and the impact of cold pools on extreme rainfall are not well understood[152]. Furthermore, convective organization is related to a complex interaction between cold-pool dynamics and vertical wind shear[148,153]. Vertical wind shear is expected to decrease with climate change[154,155], but the resulting consequences for convective organization and extreme precipitation frequency and intensity are not well understood.

Cloud feedbacks and size effects. Cloud feedbacks and cloud-size effects have been important in super-CC apparent scaling of sub-daily rainfall intensities in several studies. Cloud systems merging into larger clouds (or rain areas) produced larger precipitation intensities[30,156,157], with the increasing height of the tropopause with climate warming allowing larger storm systems to establish[18,158]. As high rainfall intensities can be sustained only when sufficient moisture is supplied to the cloud — noting that a typical atmospheric column contains only 20–40 mm of water in the form of vapour — horizontal moisture convergence must increase at high temperatures to support super-CC behaviour. Evidence suggests that enhanced moisture convergence near the surface is strongly linked to the growth of cold pools that form owing to cold-air downdrafts caused by evaporating rain[156,159], and at greater heights owing to large-scale convergence caused by dynamical adjustments of the atmospheric motions due to latent heating[18,20]. Therefore, latent heat release, increased vertical velocities and subsequent in-cloud lateral moisture convergence through the cloud base play a key part in the intensification and size of individual storms[15,20,24,98,160,161] and explain the diversity of responses in standard-resolution climate model projections[162].

Although storm size is related to moisture convergence, some evidence suggests intensification of the core of a convective storm at the expense of rain intensities outside the core. This outcome can result in disproportionate intensification of the storm centre at high temperatures at the expense of the rain-cell area[113,114,163], also seen as a result of the urban heat island effect[135]. Yet, in a study using radar-based rainfall data for the Netherlands, disproportionate intensification was not found; instead, storm-centre intensification and an increase in storm size went hand in hand[30]. Very-high-resolution idealized model simulations also indicate stronger growth of convective cells at higher dew-point temperatures[159,164]. Thus, the existence of super-CC scaling is likely connected to rain-cell or storm size, and super-CC dependencies can be supported only when large-scale conditions allow the sufficient growth of rain cells, converging more moisture into the cloud system[30].

There are two potential effects of storm size on short-duration extreme rainfall. In order to sustain super-CC rates in a warmer climate, the cloud system has to source its moisture from larger areas. Thus, bigger systems with stronger dynamics draw in more moisture from the environment[98]. The other effect is that, at a fixed surface position, a bigger system may produce more rain, so even if the intensity scales with CC, the total rainfall over a point may exceed CC[32].

Large-scale stability, humidity and dynamics. Large-eddy simulations demonstrate that rainfall intensity depends on atmospheric stability, with a decrease in intensity as the atmosphere stabilizes, and that large-scale moisture convergence mainly governs storm size[158]. Therefore, climate change-induced stabilization of the troposphere (corresponding to the decrease in temperature with height becoming smaller[165]) is expected to slow the rate of intensification of convective storms and rainfall extremes[17,166]. High-resolution, idealized and large-ensemble modelling studies demonstrate that enhanced latent heating of the atmosphere in warmer conditions can suppress convection at larger scales[24,124], leading to an overall reduction in precipitation amounts, but pseudo-global warming case studies indicate that extreme rainfall events can still intensify[10].

Atmospheric stability is also influenced by the direct radiative-heating effect of higher CO_2 concentrations[167] and the effects of aerosols[168]. Warming from increased radiative forcing owing to declining aerosol concentrations is expected to intensify rainfall[169], although the role of radiative forcings is difficult to separate from natural variability[170]. At local scales, atmospheric heating by absorbing aerosol and the increase in cloud condensation nuclei associated with absorbing and scattering aerosol have been linked with the inhibition of warm rain and a delay and invigoration of intense rainfall and flooding[168,171]. However, the multiple processes governing future changes in atmospheric aerosol concentrations and their effects on heavily precipitating storms are highly uncertain[168,172]. CPMs indicate that changes to atmospheric stability may be key to changes in the characteristics of rainfall extremes in the future climate, and are expected to be latitudinally dependent[24,124]. In the tropics, the warming profile will be closer to moist adiabatic than constant, but moist adiabatic stratification is also likely relevant in the mid-latitudes on heavy precipitation days. A well-understood consequence of climate change is an increase in tropopause height due to the thermal expansion of the troposphere and cooling of the stratosphere[173]. This increase will result in a deepening of deep convection[174], potentially increasing surface precipitation[175]. The average low-level relative humidity is projected to decrease over most land areas[136,176], which can considerably reduce heavy rainfall rates[142]. However, relative humidity might not change in the extreme precipitation environments that typically feature moisture advection from humid regions[98]. Decreases in relative humidity will influence cold-pool dynamics by promoting the evaporation of rain and increasing convection inhibition and atmospheric instability, thereby affecting convective dynamics.

Intensification of sub-daily rainfall extremes in CPMs and daily rainfall extremes in global climate models is also partly related to changes in future large-scale dynamics[72,98,107]. For example, most 1-h precipitation extremes in the western USA arise from two coherent mid-latitude synoptic patterns, namely, disturbances propagating along the jet stream and cut-off lows[177]. Atmospheric rivers also have a role in generating precipitation extremes at short and long durations[178,179]. However, other studies have shown that regional-scale circulation, as viewed through the lens of weather types, has a large influence on the frequency and intensity of rainfall extremes, but this influence tends to weaken for shorter-duration (<6–12 h) extremes[180]. Thus, regional-scale processes and their feedback to the large-scale circulation will determine how regional precipitation intensities respond to climate change and, hence, their impact on the flood hazard.

Changes in the large-scale environment, such as atmospheric stability, absolute and relative humidity, and large-scale circulation, are non-uniform across the globe, depending on latitude but also on whether they occur over ocean or land. For example, changes in stability over tropical oceans are close to moist adiabatic[120], but the stabilization over the mid-latitudes can be partly compensated for by increased surface temperatures due to surface drying[110].

Implications for flood hazard

It is not simple to relate changes in extreme rainfall to changes in floods, which can be caused by a multitude of drivers that range from long-duration and short-duration rainfall events to snowmelt, rain-on-snow events and/or elevated storm tides[181–184]. For example, serious floods recorded across Europe and Asia have been linked to persistent atmospheric circulation patterns[185–187]. Floods triggered by sub-daily rainfall extremes can be classified as either ‘short-rain’ (several hours to a day) or ‘flash’ (<90 min) floods[48,183], with the latter being particularly hazardous[188], owing to their rapid onset and, therefore, the difficulty in providing early emergency warnings[189,190]. Small mountainous catchments and urban catchments are often highly sensitive to sub-daily

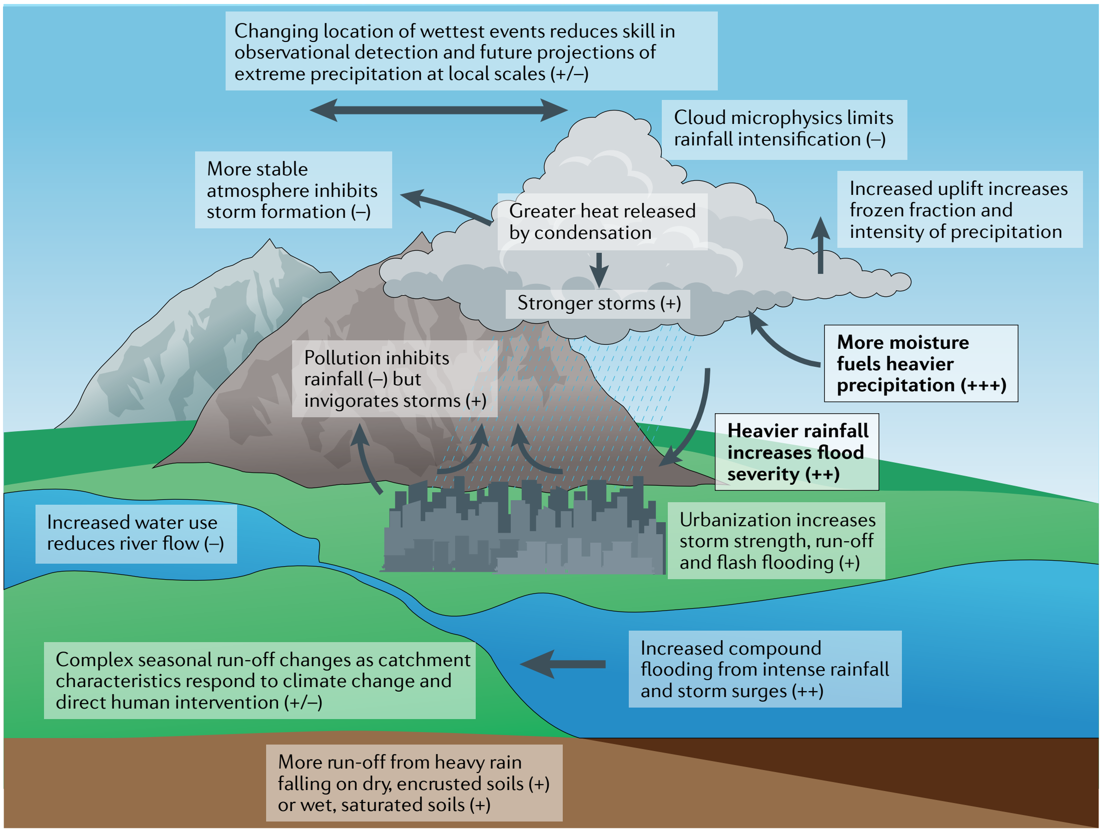

Fig. 6 | **Important processes driving changes in sub-daily extreme precipitation and flooding.** Schematic illustrating the factors contributing to changes in sub-daily precipitation extremes and the flood hazard, with contributions to increases (+) and decreases (–) marked. The most dominant processes with the highest certainties are indicated in bold. Adapted from REF.[224], CC BY 4.0.

rainfall extremes, with rainfall responsiveness determined by catchment size, terrain, vegetation and the degree of imperviousness and channelization[8].

First-order approximations from flood theory suggest that both the volume and the peak flow rate (and, consequently, the height, areal extent and momentum) of the flood could be expected to increase non-linearly with increasing catchment-average extreme rainfall intensity. In the case of flood volume, as rainfall intensity increases, proportionally more rainfall can be expected to convert to the flood hydrograph ('excess rainfall'), rather than be intercepted by vegetation or absorbed into the soils and other catchment storages[191,192]. Furthermore, flood peaks often increase non-linearly with an increase in excess rainfall, owing to increasing velocities with increasing discharge[193]. However, the above expectation assumes stationarity of all other flood-generation processes, which is unlikely to be true as the climate changes[194]. Other relevant factors that may also be subject to climatic changes include rainfall temporal patterns[56,195] and antecedent catchment conditions[196–198], as well as interactions between sub-daily rainfall extremes and other processes such as snowmelt[199] and storm surge[200–202] as part of 'compound' flooding events[203,204].

Owing to the complexity and diversity of flood-generation processes and direct human influence on catchment characteristics (FIG. 6), it is not possible to directly extrapolate the intensification of sub-daily rainfall to changes in flood hazard, leading to a focus on empirical and process-based modelling evidence. Although, on average globally, more stations exhibit decreasing trends than increasing trends in daily discharge, this pattern is reversed for the smallest two catchment categories (areas <390 km^2)[205]. This finding is consistent with (but not conclusive evidence for) the hypothesis that sub-daily rainfall intensification is translating into a commensurate intensification of short-rain and flash floods. Most regional studies of flood trends also focus on daily or longer timescales (for example, see REF.[205] for a summary of regional studies of flood trends), with only one study at the sub-daily timescale exploring the atmospheric mechanisms that lead to flash floods[206]. A major challenge for empirical studies is the relative lack of streamflow data at sub-daily scales and/or for small catchments; for example, only 21% of the Global Streamflow Indices and Metadata Archive record[207] — currently the largest record of historical streamflow globally — is for catchments smaller than 100 km^2. Furthermore, for urban catchments, it is particularly challenging to attribute changes in floods to rainfall intensification, owing to the urbanization that is likely to have occurred over the recording period[208]. These challenges limit the capacity to make definitive statements on whether intensification of sub-daily rainfall can be detected in streamflow records using empirical data alone.

Modelling studies potentially represent an alternative line of evidence for changes to flooding due to sub-daily rainfall. There are now several studies predicting changes in flood hazard and/or risk at the global scale using daily global hydrological model simulations[209–212]. However, these models have yet to be applied at sub-daily resolutions, owing to the absence of a reliable global atmospheric forcing data set at the sub-daily timescale[213], considerable challenges in modelling the key hydrological processes and calibration difficulties as the spatial and/or temporal resolutions increase (see REFS[214,215] for reviews on state-of-the-art global hydrological modelling efforts). By contrast, local-scale studies focusing on individual catchments suggest that sub-daily rainfall increases will translate into increased flood risk[49,216,217], but these findings are difficult to generalize to the global scale.

Synthesizing a conceptual framework

Observations, modelling experiments and regional apparent temperature scaling indicate an intensification of heavy rainfall extremes, with warming at a rate consistent with the increase in atmospheric moisture (the thermodynamic CC rate). However, there is evidence from observed trends and apparent temperature scaling of stronger increases in short-duration extreme rainfall intensities than expected from atmospheric moisture increases alone (super-CC changes). Thus, sub-daily rainfall intensities may increase with warming at rates greater than CC. CPMs also indicate higher intensifications in short-duration extreme rainfall intensities for rarer events with global warming.

Idealized and full-scale CPM experiments have identified some mechanisms behind localized super-CC intensification of sub-daily precipitation extremes. This intensification is likely due to enhanced latent heat release, increasing buoyancy in convective clouds, increased updraft velocities and increases in moisture convergence, producing larger storms (FIG. 5), which can also be observed as effects of the urban heat island in cities. Increases in atmospheric stability towards a moist adiabat in the mid-latitudes with warming are expected to dampen these increases, and, in the tropics, the warming profile is expected to be even closer to a moist adiabat. Moreover, changes to relative humidity affect rain intensity in various and uncertain ways by influencing the triggering of convection, cold-pool dynamics, cloud entrainment and atmospheric stability. The role of changes to large-scale atmospheric circulation dynamics is clearly important but not well researched, with important potential control over static stability and CAPE. The discrepancies between the results of CPM studies under radiative–convective equilibrium and more realistic regional CPM studies indicate the importance of large-scale dynamics in the responses of short-term extreme precipitation to global warming. However, atmospheric dynamics likely have a greater impact on longer-duration extreme rainfall intensities and frequencies than short-duration storms, although they have an important role in providing moisture to initialize and sustain intense convective systems.

It remains unclear whether storm size will increase with warming, with conflicting findings from different regions. Despite this uncertainty, both observational and modelling studies indicate increases in the peak intensity of storms with warming, although historical rainfall intensification is, so far, small compared with the projected intensification over the twenty-first century. This increase in peak intensity coupled with an increasing storm footprint could compound to cause substantial increases in total event rainfall in some regions, with a high-emission-scenario study for the USA predicting a doubling of the heavy precipitation volume of future mesoscale convective systems by the end of the twenty-first century[98]. Evidence also suggests that large-scale convergence of moisture mostly affects storm size or frequency, with a smaller effect on intensity.

There is limited evidence of correspondence between the response of precipitation intensities to day-to-day climate variability and their response to warming. Therefore, the relevance of present-day apparent scaling to climate change is questionable. Understanding precipitation scaling with surface air temperature is hindered by confounding effects that can cause negative apparent scaling: moisture limitations, the influence of seasonality, mixing of rain types and weather regimes, as well as feedbacks from the storm itself. Apparent scaling with dew-point temperature, as a direct proxy for humidity, removes some local dynamical factors and produces more consistent scalings close to, or above, CC, and, in limited studies so far, shows greater correspondence with climate scaling in CPM simulations. An important additional confounder is change to large-scale circulation, but for changes to short-duration precipitation intensities, atmospheric state variables (such as humidity) are probably more relevant. Therefore, dew-point temperature scaling is likely more appropriate for interpreting change to short-duration extremes, but care must still be exercised because large-scale circulation sets up an atmospheric state (stability, humidity and wind shear) in which convective systems develop. Finally, the change in atmospheric dry lapse rate towards more stable conditions in the future climate could lead to smaller increases in sub-daily rainfall intensities than those derived from apparent scaling. For apparent scaling to provide a guide to climate scaling, there are two requirements. First, the temperature-scaling variable needs to be physically (and statistically) tied to rainfall extremes, such that short-duration precipitation extremes can be well described on the basis of only the thermodynamic environment of the storm; in this regard, dew-point temperature (as a measure of humidity) is central in explaining the future intensification of rainfall extremes. Second, other properties of the atmospheric environment, namely, atmospheric stability, relative humidity and large-scale circulation, must co-vary similarly between day-to-day variations and long-term climate change; this is not proven and is particularly unlikely in the tropics.

Hazardous flooding is likely susceptible to intensification of sub-daily extreme rainfall, particularly at short timescales, but there is still limited quantitative evidence. Although most regional flood-trend studies focus on daily or longer timescales, evidence is emerging that sub-daily rainfall intensification is related to an intensification of flash flooding, at least locally. This recent signal emergence may be expected, as historical rainfall intensification is small compared with projected changes by the end of the twenty-first century. Moving forward, the flood hazard may be dominated more by rainfall change than is seen in the historical record, but, owing to the complexity of the flood-generation process, direct extrapolation is not possible. As short-duration extreme rainfall intensification is expected to increase flood hazard non-linearly, and urban heat island effects further enhance this intensification, global warming likely has serious implications for flash flooding globally, particularly in cities, and this requires urgent climate change adaptation measures.

Future perspectives

Huge advances have been made in understanding and predicting changes to sub-daily rainfall extremes. A coordinated data-collection effort by the international community has yielded the first global data set of sub-daily rainfall observations[27], with more than 25,000 stations available (with 16,000 having more than 10 years of data). Open-source code is available for quality control, and sub-daily precipitation indices are being produced to complement the Expert Team on Climate Change Detection and Indices (ETCCDI) daily precipitation indices. The new quality-controlled GSDR data set and sub-daily precipitation indices have great potential in improving existing merged data sets such as Multi-Source Weighted-Ensemble Precipitation (MSWEP)[218,219], in developing radar-gauge data sets and in evaluating satellite products and CPMs.

There have been corresponding large advances in CPM modelling. CPMs offer a promising avenue for investigating and explaining mechanisms, as they can simulate sub-daily rainfall extremes more realistically than do traditional climate models that rely on deep convection parameterizations. However, realistically simulating the change in sub-daily rainfall extremes depends on capturing multiscale processes that span the microscale to the global scale. Although some of these processes are better understood (for example, the increase in atmospheric moisture and stability), others are highly uncertain (for example, changes in precipitation efficiency, cloud entrainment and cloud–aerosol interactions). Promising developments are the emergence of global CPMs[220], the first ensemble of projections at convection-permitting scales[91] and coordinated CPM intercomparison projects[221], which will allow a spatio-temporal, multiscale assessment of precipitation extremes and an improved understanding of uncertainties in sub-daily extreme rainfall projections. It may also be advantageous to use CPMs to evaluate the relationship between apparent scaling and climate scaling for different regions.

Although a large literature on temperature scaling exists, most studies use near-surface air temperature to derive the apparent scaling[22,23]. Growing consensus points to the importance of including moisture in the assessments[61], as near-surface air temperature changes generally exceed dew-point temperature changes, reflecting decreases in relative humidity with warming[125]. Scaling with dew-point temperature, as a direct proxy for humidity, thereby reduces the mismatch between temperature and humidity and its relation with atmospheric circulation. However, even an average daily dew-point temperature may not be appropriate for scaling, as changes in the diurnal timing of convection mean that the absolute humidity (dew-point temperature) increase at the time of the rainfall event is less than what would be expected based on the mean changes[222]. To be able to use apparent scaling in a climate change context, careful analysis of the absolute humidity increase for the environment of the clouds is still needed, as well as the co-variation of other properties of the atmospheric environment. Careful interpretation of apparent scaling of extreme precipitation must, then, be effectively combined with process understanding and detailed modelling to evaluate the likely responses under climate change.

Although much progress has been made, observational and model understanding of changes to sub-daily precipitation extremes must be further developed through a common framework. Global-scale analyses using consistent methodologies may provide a coherent picture of change in response to warming. Currently, studies cannot be easily compared and differences may occur for physical reasons or from statistical and/or methodological incompatibilities. We recommend that a moisture component, such as dew-point temperature, must be included in temperature-scaling studies or other methods applied to remove meteorological factors that are related to local-scale processes, rather than climate change response. Global studies[11] should be performed using common, robust and repeatable methods to examine apparent scaling at different durations and spatial scales. At the same time, we recommend coordinated pseudo-global warming or full CPM experiments over common domains, with the same forcing or perturbation and at the same resolution, to provide robust intermodel comparisons. This comparison would establish whether there is a scale at which model projections start to converge to similar projections, particularly in relation to precipitation extremes. Another promising avenue of research is the exploitation of transient CPM simulations; for example, ensemble CPM simulations for the full 100-year period from 1980 to 2080 have been carried out at the UK Met Office as part of the UK Climate Projections project[91]. These new simulations will help connect the analysis of present-day variability from observational studies with long-term climate change projections from models.

Links between changes to rainfall extremes and flooding are not well established, even at longer durations, such as daily. Observed increases in the intensity of precipitation extremes have not led to the expected increases in flooding. To connect changes in short-duration rainfall extremes to flooding, we recommend a continued focus on expanding observational data sets (particularly as they relate to sub-daily streamflow events, but also the various drivers of sub-daily floods) and supporting model developments by including better forcing data sets at the sub-daily timescale (for example, a reliable global sub-daily precipitation product). This approach would require commensurate increases in the spatial and temporal model resolution and consideration of the representation of run-off-generation processes[191] of large-scale hydrological models, recognizing that there are often complex scaling effects between the small-scale catchments most vulnerable to flash floods and the larger-scale basins that are often the focus of these modelling efforts. Additionally, as the occurrence of flash floods depends on intense rainfall rates at small spatial and temporal scales, the clustering of convection could have a major role in determining the likelihood of such floods. Global climate models and even CPMs do not sufficiently resolve such clustering. Understanding how clouds organize non-randomly in space is a future challenge that could be tackled by improvements in CPM resolution and increased theoretical understanding of cloud-interaction processes.

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Author contributions
H.J.F. led the writing of the manuscript, the figure contributions and coordinated all contributions. G.L. led the section on temperature scaling and designed Fig. 2. A.F.P. led the review of convection-permitting modelling and designed Fig. 5. S.W. led the section on flood hazard. E.L. designed Fig. 1, R.P.A. designed Fig. 6, S.B. designed Fig. 4, and P.B. and J.O.H. designed Fig. 3. All authors discussed the content and contributed to the writing of the manuscript.

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