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Anthropogenic intensification of short-duration rainfall extremes

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Key Messages:

- **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 modeling, 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 due to modulation by changes to temperature stratification and large-scale atmospheric circulation**

- **The evidence is unclear whether storm size will increase or decrease with warming; however, increases in rainfall intensity and the spatial footprint of the storm can compound to give significant increases in 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 will have serious implications for flash flooding on much of the planet and requires urgent climate-change adaptation measures.**

Abstract

Short-duration (1 to 3 hour) 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 their intensification, the drivers and the likely impacts on flash-flooding. Short-duration rainfall extremes are intensifying with warming at a rate consistent with atmospheric moisture increase ($\sim 7\%/K$) that also drives intensification of longer-duration extremes (1day+). Evidence from some regions indicates stronger increases to short-duration extreme rainfall intensities than expected from moisture increases alone. Idealized modelling studies suggest these stronger local increases are related to convective cloud feedbacks but their relevance to climate change is uncertain. 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 increased storm spatial footprint to significantly increase total event rainfall. These findings call for urgent climate-change adaptation measures to manage increasing flood risks.

1. Introduction

Intensification of the hydrological cycle is one of the known impacts of a warming climate, with rainfall extremes increasing over recent decades^{1,2,3}. However, uncertainty remains in understanding changes to rainfall extremes, particularly for short-duration (1-3hr), relatively small-scale (10s of km or less), convective events. Changes to rainfall extremes have been assessed based on 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 return period). While changes in frequency and intensity have the same sign, the amplitude of the change differs depending upon the shape of the rainfall distribution. Usually, changes to the frequency of the most extreme events exceed those of the intensity changes - a property which is tied to the distribution of rainfall extremes⁴.

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 $\sim 7\%$ 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 actual humidity of the air also increases at roughly the same rate^{5,6}. Since 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 relation⁷.

Several studies have confirmed an approximately CC rate of increase in observations and projections of daily extreme rainfall^{1,2,8,9,10} when averaged globally, while 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 worldwide¹¹. However, for sub-daily intensities some studies suggest an increased sensitivity to warming, with the existence of super-CC scaling (scaling rates larger than $7\% K^{-1}$) in some locations^{12,13,14,15,16}. Evidence shows that physical processes, particularly related to convective clouds, can plausibly explain super-CC scaling rates. Suggested mechanisms that could lead to this enhanced sensitivity are dynamical feedbacks in cloud core updrafts^{7,17,18}, cloud-cloud interactions driven by cold pools¹⁹ and quasi-geostrophic large-scale vertical uplifting^{20,18}. However, it is uncertain whether this observed super-CC scaling will translate into a similar climate change sensitivity or ‘climate’ scaling.

Multiple new studies have examined changes to sub-daily rainfall extremes, ranging from convection-permitting modelling^{21,22,23,24} and idealized model experiments¹⁸ to assessments of observations^{1,25}. An effort updating the state of knowledge on the topic has been coordinated through the INTENSE (INTElligent use of climate models for adaptatioN to non-Stationary hydrological Extremes) crosscut²⁶ 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 (the Global Sub-Daily Rainfall (GSDR) dataset²⁷, see Fig. 1), producing new insight into the global climatology of sub-daily precipitation extremes from gauge data²⁸. Alongside this advance has been the development of new satellite retrieval methods for precipitation and regional-scale radar datasets. Together, these datasets have been used to quantify the effects of changes in temperature and humidity on precipitation extremes at different time-scales, links between the frequency and intensity of heavy rainfall and large-scale circulation variability²⁹ and local changes to the spatial structure of intense storms³⁰. However, despite this new understanding from observations of 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 allowed sub-daily, and even sub-hourly, precipitation extremes to be represented over continental-scale areas on (multi)decadal time scales^{24,21,31,32,33} (see Fig. 1 for continental-scale domains available at <5km horizontal grid spacing). 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^{34,35,31,36}, orographically-enhanced extreme precipitation^{37,38,35,39} and scaling relations⁴⁰. CPM simulations use two main approaches. Firstly, pseudo-global warming^{41,42,43} (PGW), where a storm's environment is perturbed by mean climate change signals typically derived from Global Climate Models (GCMs). PGW 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}. Secondly, full downscaling of coarser-resolution climate model simulations to provide more realistic characteristics of sub-daily rainfall⁴⁶ 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 impacts, while super-CC scaling would have a greater effect⁴⁷. 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 networks⁵⁰. Cities are particularly vulnerable to floods generated by heavy short-duration rainfall since their infrastructure systems were built during the last centuries based on historically lower rainfall intensities, with a subsequent increase in impermeable surfaces; this provides a need for 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 insights from very 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 was something that was not possible previously⁸. This allows us to propose a conceptual framework for understanding the intensification of short-duration rainfall extremes and to assess the implications for flood risks. Finally, we provide some comments about gaps in our current knowledge and how we might address these.

2. Temperature Scaling of Extreme Rainfall Intensities

Since 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’ scaling⁵¹ – 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^{12,52,53,54,55}, temperature measurements and rates (maximum, mean or interval ahead of rainfall) used complicate the interpretation of scaling results.

Studies indicate that daily extremes mainly show CC-scaling^{3,2} but super-CC scaling ($> 7\%/K$) appears in some locations (for example Australia, the Netherlands, Hong Kong) for extreme hourly or shorter accumulations. Fig. 2 illustrates these apparent scaling relationships for the Netherlands. Scaling strongly depends on the temperature measurements used, with near-surface air temperature commonly producing CC or super-CC scaling rates for hourly rainfall at low to moderate temperatures (from 10-20 °C), but negative rates at moderate to high temperatures ($>20-25$ °C)^{56,57,8,58}. Negative scaling at high near-surface air temperatures is (partly) explained by drier conditions necessary to generate the hottest temperatures and limited moisture availability on warm days^{12,59,60,16,14}, where high-pressure situations are characterized by high temperatures and low (relative) humidity^{40,61}. Including moisture in the assessment⁶⁰, by use of dew-point temperature⁵⁹ (Fig. 3a), produces greater consistency in scaling across regions and temperature regimes, with dependencies close to CC or above, even in the Tropics^{11,13,14,62,63}.

The use of temperature-scaling to project change to extreme precipitation with future warming is complex^{64,51}. Understanding the processes behind super-CC scaling may allow the exclusion of systematic dependencies not relevant for climate scaling. For example, present day scaling may alias changes in meteorological regimes (e.g. stratiform to convective rain types) with temperature^{15,65} (see Fig. 3b) or the mixing of large-scale and local forcing, particularly if large-scale flow conditions vary substantially between seasons^{64,66}. The reversal of causal relations whereby intense rainfall is itself the cause of temperature variations^{51,60,59,67} may also influence apparent scaling. Despite these complications, temperature-scaling may perhaps be expected to be similar for short-term variability and future (and past¹³) warming when sampling consistent meteorological regimes and by considering the influence of moisture and latent heat release^{17,68}. However, changes to temperature stratification in the atmosphere and to large-scale (or even mesoscale) circulation variability^{69,70} can also strongly affect extreme precipitation intensities but are not strongly connected to apparent temperature-scaling.

3. Changing character of sub-daily rainfall extremes

3.1 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, Australia¹, parts of China⁷¹, SE Asia⁷², Europe^{73,74}, and North America⁷⁵. Fig. 4 updates^{8,76} and summarizes existing analyses of change from rain gauge observations. The understanding of changes across large areas of the globe has been inhibited by either a lack of data or lack of access to it and, even where data exists, the nature and extent of quality control checks on sub-daily rainfall data is not always apparent. Further, a significant minority of studies identified in Fig. 4 only consider local-scale changes⁷⁷ based on 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 due to the application of a wide range 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/seasonal). This includes, in some instances, the use of relatively short periods of observations which means results may be sensitive to natural variability rather than representative of long-term change⁷⁸. The predominantly positive trends over the U.S., Europe and Australia are consistent with the earlier initial review⁸; 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 we now see evidence of increases over most of eastern China and decreases in the north. Several new studies also point to increases over southeast Asia, but across the U.K., 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^{79,80}. Furthermore, even where trends are examined across regional and national scales, few studies consider the field significance of any observed changes (see ⁷⁵ for an example of field significance testing). Thus, identifying the most appropriate methodologies for robust detection of rainfall change emerges as a significant issue. Although many observation-based change detection studies identify and discuss warming as a potential mechanism for increased event frequency/intensity, relatively few actually test this hypothesis, or consider observed changes in the context of other potential drivers⁷⁸. Figure 4 therefore identifies studies where sub-daily rainfall trends/changes are analyzed in the context of either observed temperature change or scaling¹³, large-scale circulation and modes of variability⁷⁸, or the potential influence of urbanization, through increases in anthropogenic aerosols⁸¹ or the urban heat island effect⁸², which is emerging as an interesting research area.

In some studies, intensification has been shown to exceed thermodynamic expectations. For instance, peak intensities of extreme hourly rainfall are intensifying more rapidly than would be expected with global mean warming in Australia¹, at up to 3 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 since 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^{25,18,83}, albeit with potentially low statistical certainty due to short record lengths⁸⁴. Evidence has also been found, mainly in tropical locations, for a strengthening of precipitation systems and significant effects of warming on peak intensities in urban areas^{85,86}, with intensification of peak intensities and frequencies of hourly extreme precipitation tending to occur downwind of urban areas in mid-latitude locations such as the US Mid-west⁸⁷.

Results from convection-permitting models 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^{21,22,23,24,88,89,90,91,92}. Mesoscale models also find super-CC scaling of future intensities⁶⁸. 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^{23,93}. At the same time, moderate and light rainfall hours are projected to decrease in frequency⁹⁴, resulting in future climates that are more favorable for both droughts and floods concurrently^{22,24,95,96}. This relation is physically understandable since global precipitation is constrained by the global energy budget to increase more slowly than extreme precipitation thereby requiring sub-CC or even decreases in precipitation away from the wet regimes⁹⁷; an observational study⁹⁸ also found more intense peak rainfall at the expense of total rainfall at higher temperatures in Australia, regardless of the climatic region and season.

PGW 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 the CC scaling^{91,99,100,101,102,103}. Similar results have been found for flood-producing mesoscale convective systems^{104,105,106} (MCSs) in the U.S. and extreme rainfall in the Netherlands which

feature super-CC increases^{107,108}. These large increases have been partly related to more vigorous updrafts in the U.S. cases, but assessing uncertainties in convection-permitting simulations remains challenging

Differences in statistical approaches (for example, using conditional percentiles⁵⁵) 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 vs orographic) also likely play an important role. Despite this, the signal of extreme rainfall intensification is robust across different climate types, latitudes and CPM structures¹⁰⁹. CPM simulations indicate that sub-daily rainfall extremes are likely to intensify in regions and seasons where moisture supply is not limited^{23,110}. However, a fixed temperature threshold above which precipitation is limited by moisture availability is not supported by modelling evidence^{4,23}.

3.2 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 warmer temperatures, precipitation events increase their peak intensity and become smaller in size in Australia¹¹¹ and Germany¹¹² but increase their peak intensity and become larger in the Netherlands³⁰. This increase in storm size with climate warming is also shown in CPM pseudo-warming experiments for the U.S.⁹⁵. For the UK, CPM simulations show peak intensity increases and storms becoming longer in duration with warming³² 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^{104,113}. MCSs are the main cause of extreme precipitation in the eastern U.S.¹¹⁴. Hourly rainfall volumes from extreme MCSs might increase at much faster rates than CC due to a combination of close to CC increases in hourly peak rainfall rates and a spread of the heavy rainfall area⁹⁵. This increase in peak intensities and spatial footprint of storms in a warming climate might result in even higher increases in total 'event' rainfall^{95,99}. Increased moisture advection into future MCSs and changes in the cloud microphysics are possible causes for the rapid increase in precipitation volume but further work is needed to understand the robustness of these results. The amplitude of the diurnal cycle of surface temperature, not just its mean or maximum, might also help MCSs to develop¹¹⁵.

4. Disentangling drivers of change

The rate of intensification of rainfall extremes under climate change depends on various processes that range from micro- to synoptic- and planetary-scales. New observational and CPM studies have enhanced our 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, which is close to or slightly below CC scaling^{23,99,105}. However, enhancing or damping this increase are several dynamical changes at small and large scales⁶⁹. Idealized model experiments^{17,18} and CPMs in pseudo-global warming experiments^{107,108,68} indicate feedbacks through enhanced latent heating with warming can lead to a super-CC response^{116,117,17} for short-duration rainfall extremes. However, this response also depends strongly on stability changes of the atmosphere^{44,118}, with closer to CC dependencies and no evidence for dynamical invigoration of precipitation extremes when atmospheric stability changes follow a moist adiabatic lapse rate^{17,119,120}. Storm intensification at the cloud-scale combined with stability increases at larger time- and space-scales thus suggest extreme rainfall responses to warming are time and space dependent¹²¹. We therefore split our explanation of process interactions into three parts, dependent on spatial scale. Fig. 5 provides a schematic summarizing our new understanding of feedback processes affecting rainfall extremes and the key findings, mainly from model projections.

4.1 Cloud-Scale Dynamics and Microphysics

Atmospheric stability (vertical lapse rate) plays a key role in how convective systems respond to climate change. The intensity of convective storms is related to the Convective Available Potential Energy (CAPE) in both CPMs^{122,123,124} and observations²⁸. Climate models¹²⁵ and radiative-convective equilibrium modelling experiments^{126,127,128} project that CAPE will increase thermodynamically with warming, implying strong increases in the future frequency of occurrence of environments conducive to intense thunderstorms¹²⁹. This increase in CAPE implies systematic deviation of the thermal stratification of the atmosphere from a moist adiabatic lapse rate that is non-negligible at high temperatures¹²⁶. Increased CAPE, reflecting larger buoyancy in convective clouds resulting from enhanced latent heating, could then lead to super-CC behaviour^{116,117,17}; yet evidence for stronger updrafts is still limited. However, even when CAPE and updraft velocities increase with warming, precipitation extremes may not produce super-CC scaling because the vertical profile of motion matters^{130,131}. Urban heat islands also have an effect on extreme rainfall intensities, creating a more unstable atmosphere, increased vertical uplift and moisture convergence, sustaining a local circulation initiated by the relative warmth of the urban area¹³².

However, thermodynamic increases in stability and reduced continental relative humidity¹³³ increase convective inhibition and prevent low-level buoyant air from ascending^{96,134}. Cloud mixing could lead to smaller changes in buoyancy than CAPE changes would imply¹²⁶. This effect will suppress weak and moderately intense convection from forming due to more effective entrainment reducing buoyancy in a warmer atmosphere¹²⁶, although the intensity of strong convection²⁴ may be enhanced due 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 processes¹³⁵, resulting in too strong updrafts and too high precipitation intensities at the surface^{136,137}. Idealized modeling results show that resolving entrainment demands large-eddy simulation¹³⁸ (LES, grid spacings ~200 m). Simulating entrainment processes realistically is critical to preserve realistic cloud properties and therefore for rainfall even more so under conditions of decreasing relative humidity in a future climate¹³⁹.

Climate change will also affect the cloud microphysics¹⁴⁰. The more intense convection in future climates will result in a higher ratio of graupel and hail in the cloud^{146,95,141}, which can enhance downdraft velocities and precipitation rates. Since hail and graupel will develop at higher altitudes but encounter enhanced melting before reaching the surface due to an increase in the tropospheric melting level height^{46,95}, this will likely increase the liquid water content in future clouds, resulting in a more active warm rain process and enhanced surface precipitation⁴⁵. However, uncertainties remain: the process might be different for different regions (for example, the tropics), and probably also depends on model microphysics scheme. Modelling evidence has shown that increases in convective rainfall extremes are partly controlled by microphysical processes involving droplet/ice fall speeds; super-CC scaling could hence be the result of differences in ice/liquid fall speeds^{142,140}. Changes in precipitation efficiency are also closely related to changes in cloud microphysics, changes in entrainment, and convection dynamics. A study on precipitation efficiency at convective scales for a long record of observations in the tropics¹⁴³ found that precipitation efficiency increases with precipitation rate and mid-tropospheric humidity and decreases with increasing CAPE and surface temperature. However, these efficiency differences do not directly translate to changes in precipitation intensity due to compensating changes in cloud updraft velocities¹⁴³. Climate change effects of precipitation efficiency are uncertain, with changes in efficiency found at different temperatures¹⁴² and some evidence of increases in efficiency with warming in small domains, although this is complicated by changes to convective organisation¹⁴⁴.

Cold pools appear to be a crucial part of the dynamics of convective clouds and how they respond to warming¹⁴⁵. Changes in downdrafts are related to changes in cold pool strength¹⁴⁶ with wider and deeper

clouds developing as a result of stronger cold pool dynamics^{19,147}. Cold pools also likely mediate the "communication" between convective clouds, and thereby the initiation of new convective cells through the 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 pools¹⁴⁸. Climate change impacts on cold pool characteristics are highly uncertain and their impacts on extreme rainfall are not well understood (Prein et al. accepted). Furthermore, convective organization has been found to be related to a complex interaction between cold pool dynamics and vertical wind shear^{145,149}. Vertical wind shear is expected to decrease with climate change^{150,151} but the resulting consequences for convective organization and extreme precipitation frequency and intensity are not well understood.

4.2 Cloud Feedbacks and Size Effects

Cloud-feedbacks and cloud-size effects have been shown to be important in super-CC scaling in several studies. Cloud systems merging into larger clouds (or rain areas) have been found to produce larger precipitation intensities^{30,152,153}, with increasing height of the tropopause with climate warming allowing the establishment of larger storm systems^{154,18}. Since high rainfall intensities can be sustained only when sufficient moisture is supplied to the cloud – noting that a typical atmospheric column only contains between 20-40 mm of water in the form of vapor – it is clear that horizontal moisture convergence must increase at high temperatures to support super-CC behavior. Evidence suggests that enhanced moisture convergence is strongly linked to the growth of cold pools that are formed due to cold air downdraughts caused by evaporating rain^{155,152}, or to large-scale moisture convergence^{18,20}. Therefore, latent heat release, increased vertical velocities and subsequent in-cloud lateral moisture convergence through the cloud base play a key role in the intensification and size of individual storms^{15,24,156,20,95,157} and explain a diversity of responses in standard-resolution climate model projections¹⁵⁸.

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 can result in a disproportional intensification of the storm center at high temperatures at the expense of the rain-cell area^{112,111,159}, also seen as a result of the urban heat island effect¹³². Yet, in a study using radar-based rainfall data for the Netherlands this effect could not be found, and storm center intensification and storm size went hand-in-hand³⁰. Very-high-resolution idealized model simulations also provide evidence of stronger growth of convective cells at higher dew point temperatures^{160,155}. So, the existence of super-CC scaling and rain-cell or storm size is likely connected, and super-CC dependencies can only be supported when large-scale conditions allow the sufficient growth of rain cells converging more moisture into the cloud system³⁰.

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 environment⁹⁵. 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 CC³².

4.3 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 size¹⁵⁴. Therefore, a climate change-induced stabilization of the troposphere (the decrease in temperature with height becomes smaller¹⁶¹) is expected to slow the rate of intensification of convective storms and rainfall extremes^{17,162}. 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^{122,24,154} leading to an overall reduction in precipitation amounts, but PGW case-studies indicate that extreme rainfall events may still intensify¹⁰.

Atmospheric stability is also influenced by the direct radiative heating effect of higher CO₂ concentrations¹⁶³ as well as the effects of aerosols¹⁶⁴. Warming from increased radiative forcing from declining aerosol is expected to intensify rainfall¹⁶⁵, although the role of radiative forcings is difficult to separate from natural variability¹⁶⁶. 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 inhibition of warm rain and a delay and invigoration of intense rainfall and flooding^{164,167}. The multiple processes governing future changes in atmospheric aerosol concentrations and their effects on heavily precipitating storms are highly uncertain^{164,168}. Thus, atmospheric stability changes, which are expected to be dependent on latitude, may well play a key role in the behavior of rainfall extremes in the future climate, as also shown in CPMs^{122,24}. In the tropics, it is well recognized that the warming profile will be closer to moist adiabatic than constant, although moist adiabatic stratification is likely to be relevant in the mid-latitudes on days of heavy precipitation as well. 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 stratosphere¹⁶⁹. This increase will result in a deepening of deep convection¹⁷⁰, which potentially increases surface precipitation¹⁷¹. The average low-level relative humidity is projected to decrease over most land areas^{172,133}, which can significantly reduce heavy rainfall rates¹³⁹. However, relative humidity might not change in extreme precipitation environments that typically feature moisture advection from humid regions⁹⁵. Decreases in relative humidity will influence cold pool dynamics by promoting evaporation of rain, and increasing convection inhibition and atmospheric instability, thereby impacting on convective dynamics.

Intensification of sub-daily rainfall extremes in CPMs and daily rainfall extremes in GCMs is also partly related to changes to future large-scale dynamics^{105,95,69}. For example, the majority of 1-h annual maximum precipitation across the western US are linked to two coherent mid-latitude synoptic patterns: disturbances propagating along the jet stream, and cutoff upper-level lows¹⁷³. Atmospheric rivers also play a role in the generation of precipitation extremes at short and long durations^{174,175}. 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 hours) extremes¹⁷⁶. Thus, regional processes and their impact on dynamical responses will be crucial in determining how regional precipitation intensities respond to climate change and therefore their effect on 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 ocean/land. For instance, changes in stability over tropical oceans are close to moist adiabatic¹¹⁸, but the stabilization over the mid-latitudes can be partly compensated for by enhanced surface temperatures due to surface drying¹⁰⁸.

5. 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 ranging from long- and short-duration rainfall events, snowmelt, rain-on-snow events, and/or elevated storm tides^{177,178,179,180}. For example, serious floods recorded across Europe and Asia have been linked to persistent atmospheric circulation patterns^{181,182,183}. Floods triggered by sub-daily rainfall extremes

can be classified either as ‘short-rain’ (several hours to a day) or ‘flash’ (<90 min) floods^{179,48}, with the latter being particularly hazardous¹⁸⁴ due to their rapid onset and therefore the difficulty in providing early emergency warnings^{185,186}. Small mountainous catchments and urban catchments are often highly sensitive to sub-daily rainfall extremes, with rainfall responsiveness driven by catchment size, terrain, vegetation and the degree of imperviousness and channelization⁸.

First-order approximations from flood theory suggest that both the volume and 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^{187,188}. Furthermore, flood peaks often increase non-linearly with excess rainfall increase due to increasing velocities with increasing discharge¹⁸⁹. However, the above expectation assumes stationarity of all other flood generation processes, which is unlikely to be true as the climate changes¹⁹⁰. Other relevant factors that may also be subject to climatic changes include rainfall temporal patterns^{191,98}, antecedent catchment conditions^{192,193,194}, and interactions between sub-daily rainfall extremes and other processes such as snowmelt¹⁹⁵ and storm surge^{196,197,198} as part of ‘compound’ flooding events^{199,200}. Non-linear responses in flooding and its seasonality are also possible as climate evolves.

Due to the complexity and diversity of flood generation processes and direct human influence on catchment characteristics as summarized in Fig. 6, it is not possible to directly extrapolate the intensification of sub-daily rainfall to changes to 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 was reversed for the smallest two catchment categories (areas less than 390km²)²⁰¹. This 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 Table 1²⁰¹ for a summary of regional studies of flood trends], with very little published at the sub-daily timescale, except for one study exploring the atmospheric mechanisms that lead to flash floods²⁰². 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 GSIM record²⁰³—currently the largest record of historical streamflow globally—is for catchments below 100 km². Furthermore, for urban catchments, it is particularly challenging to attribute changes in floods to rainfall intensification due to the significant urbanization that is likely to have occurred over the recording period²⁰⁴. These challenges limit the capacity to make definitive statements on whether intensification of sub-daily rainfall can be detected in streamflow records based on empirical data alone.

Modelling studies potentially represent an alternative line of evidence for changes to flooding due to sub-daily rainfall. There are now a number of studies predicting changes in flood hazard and/or risk at the global scale using daily global hydrological model simulations^{205,206,207,208}. However, these models have yet to be applied at sub-daily resolutions due to the absence of a reliable global atmospheric forcing dataset at the sub-daily timescale²⁰⁹, significant challenges in modelling the key hydrological processes, and calibration difficulties as space/time resolutions increase [see ^{210,211} for reviews on state-of-the-art global hydrological modelling efforts]. In contrast, local-scale studies focusing on individual catchments suggest that sub-daily rainfall increases will translate to increased flood risk^{212,49,213}, but these findings are difficult to generalize to the global scale.

6. Summary and Future Perspectives

Observations, modelling experiments and regional temperature scaling indicate an intensification of heavy rainfall extremes with warming at a rate consistent with the increase in atmospheric moisture (the thermodynamic Clausius-Clapeyron rate of approximately 7% per degree warming near to the surface). However, there is evidence from observed trends and temperature scaling of stronger increases in short-duration extreme rainfall intensities than expected from atmospheric moisture increases alone (super-CC changes). This suggests that 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.

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 (see Fig. 5), which can also be observed as effects of the urban heat island in cities. Increases in atmospheric stability towards a dry adiabat in the mid-latitudes with warming are expected to dampen these increases, although in the tropics, the warming profile will be closer to moist adiabatic than constant. 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 important role of changes to large-scale atmospheric circulation dynamics is clear but not well-researched, with important potential control over static stability and CAPE. However, atmospheric dynamics are likely have a greater impact on longer-duration extreme rainfall intensities and frequencies than short-duration storms, although playing an important role in providing moisture to initialize and sustain intense convective systems.

Evidence is so far unclear whether storm size will increase with warming, with conflicting findings from different regions. Despite this, both observational and modelling studies indicate increases to the peak intensity of the storm with warming, although historical rainfall intensification is small so far compared to the projected intensification over the 21st century. This increase in peak intensity coupled with an increasing storm footprint could compound to cause significant increases in total event rainfall in some regions, with a doubling of the heavy precipitation volume of future meso-scale convective systems by the end of the 21st century in a high emission scenario study for the U.S. Evidence also suggests that large-scale convergence of moisture mostly affects the storm size or frequency but less so its 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 which can cause negative scaling: moisture limitations, influences of seasonality, mixing of rain types and weather regimes, as well as feedbacks from the storm itself. Scaling with dew point temperature, as a direct proxy for humidity, removes some local dynamical factors and produces more consistent sensitivities close to CC, or above, which, in limited studies so far, show 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 (like humidity) are likely more relevant. Therefore, dew point temperature scaling is likely more appropriate for interpreting change to short-duration extremes but care must still be exercised as large-scale circulation sets up the atmospheric state (stability, humidity and wind shear) in which convective systems develop. Finally, the atmospheric dry lapse rate change towards more stable conditions in the future climate could lead to smaller increases in sub-daily rainfall intensities than that derived from apparent scaling.

Hazardous flooding is likely susceptible to intensification of sub-daily extreme rainfall, particularly at short-time scales, but there is still limited quantitative evidence. Although most regional flood trend studies focus on daily or longer time scales, 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 since historical rainfall intensification is small compared to projected changes by the end of the 21st century.

Moving forward, flood hazard may be more dominated by rainfall change than seen in the historical record, but due to the complexity of the flood generation process direct extrapolation is not possible. Since short-duration extreme rainfall intensification is expected to increase flood hazard non-linearly, and urban heat island effects enhance this intensification further, global warming likely has serious implications for flash flooding in globally, and 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 led to the first global dataset of sub-daily rainfall observations²⁷, with over 25,000 stations available (some 16,000 with 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 dataset and sub-daily precipitation indices have great potential in improving existing merged datasets such as MSWEP^{214,215}, radar-gauge datasets, 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 compared to traditional climate models that rely on deep convection parameterizations. However, realistically simulating the change in sub-daily rainfall extremes depends on capturing multi-scale processes that span micro- to global scales. While some of these processes are better understood (for example, increase in atmospheric moisture and stability), others are highly uncertain (for example, changes in precipitation efficiency, cloud entrainment, cloud-aerosol interactions). Promising developments are the emergence of global CPMs (Stevens et al. 2019), the first ensemble of projections at convection-permitting scales⁸⁸, and coordinated CPM intercomparison projects²¹⁶, which will allow a spatiotemporal multi-scale 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 spatially.

Although a large literature on temperature scaling exists, most studies use near-surface air temperature to derive the apparent scaling^{23,22}. Growing consensus points to the importance of including moisture in the assessments⁶⁰ as near-surface air temperature changes generally exceed dew point temperature changes, reflecting decreases in relative humidity with warming¹²³. Scaling with dew point temperature, as a direct proxy for humidity, thereby reduces 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 since changes in the diurnal timing of convection mean that the actual humidity (dew point temperature) increase at the time of the rainfall event is less than what would be expected based on the mean changes²¹⁷. To be able to use scaling in a climate change context, careful analysis of the actual humidity increase for the environment of the clouds is still needed. Careful interpretation of present day scalings of extreme precipitation with warming 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/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 studies¹¹ 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 PGW or full CPM experiments over the same domain(s), with the same forcing/perturbation, and at the same resolution to provide robust intermodel comparisons. This 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 1980-2080 have been carried out at the UK Met Office as part of the UK Climate Projections project⁸⁸. 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 less 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 datasets (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 datasets at the sub-daily timescale (for example, a reliable global sub-daily precipitation product). This would require commensurate increases in space/time model resolution and consideration of the representation of runoff generation processes¹⁸⁷ 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, since flash flood occurrence depends on intense rainfall rates at small spatial and temporal scales, the clustering of convection could play a major role in determining the likelihood of such floods. GCMs and even CPMs do not sufficiently resolve such clustering. Understanding how clouds organize non-randomly in space is a future challenge which could be tackled by improvements in CPM model 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 produced Fig. 2. A.P. led the convection-permitting modelling review and produced Fig. 5. S.W. led the section on flood hazard. E.L. produced Fig. 1. R.P.A. produced Fig. 6. S.B. produced Fig. 4 and the supporting information. P.B. and J.H. produced Fig. 3. All authors discussed the review paper and co-wrote the manuscript.

Figures

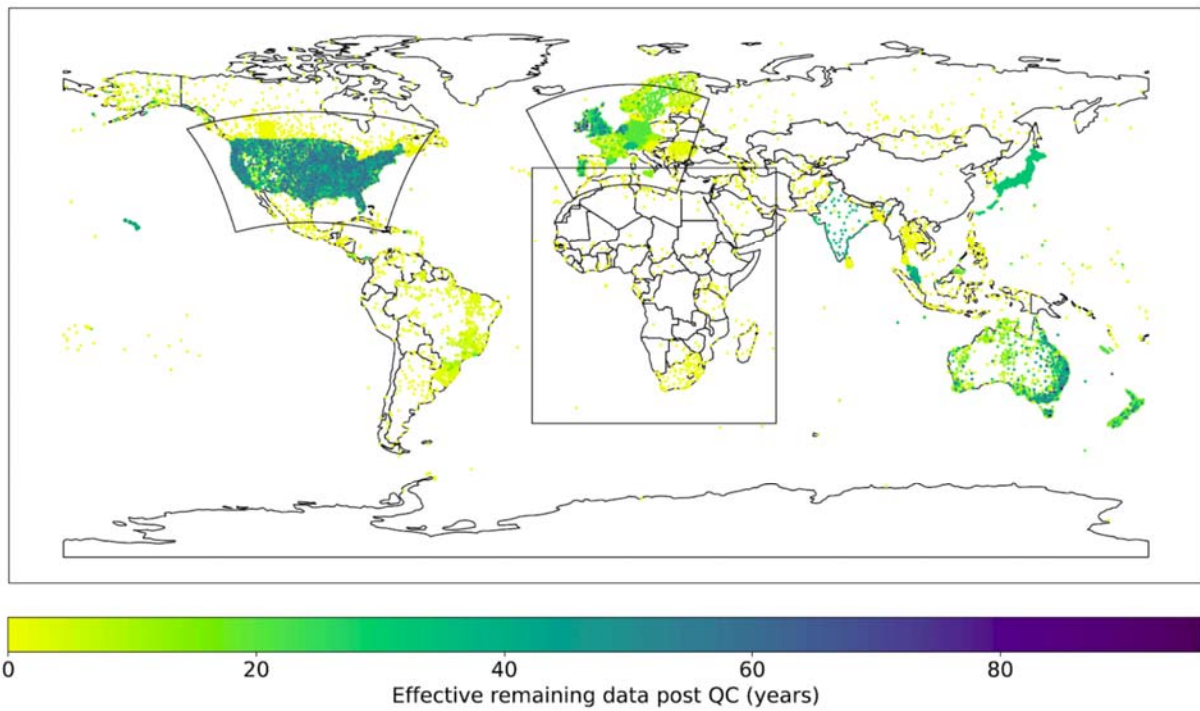


Figure 1: Hourly gauge record length remaining in the Global Sub-Daily Rainfall (GSDR) observed sub-daily precipitation dataset²⁷ after quality-control (colored dots indicate gauge locations and record length) overlain by current continental-scale convection-permitting model (CPM) domains (enclosed by black lines).

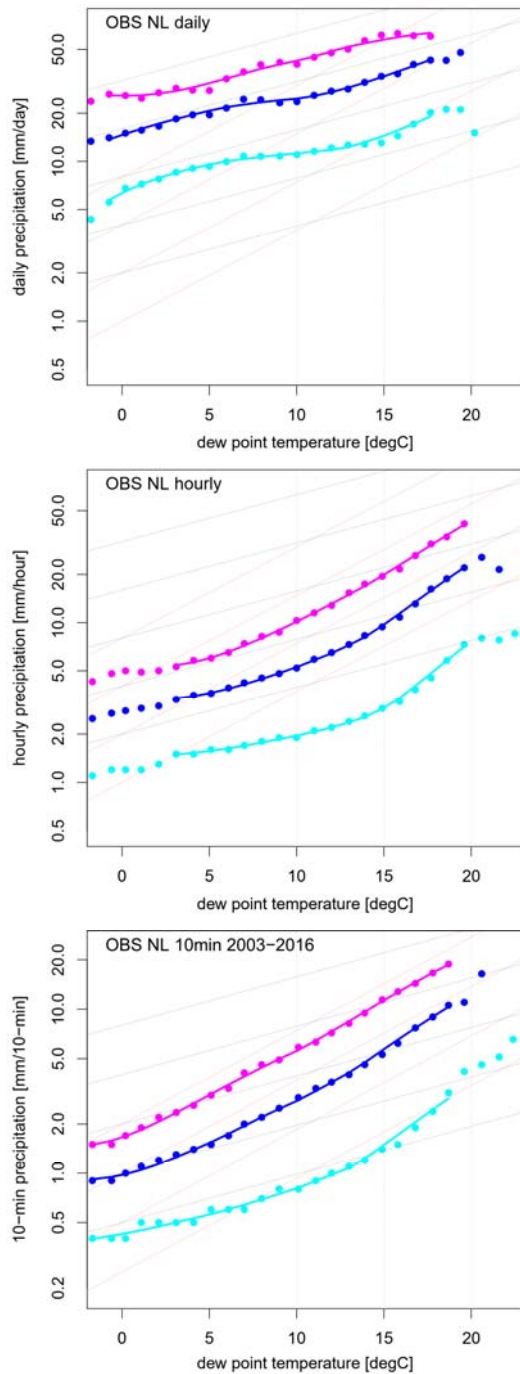


Figure 2: Scaling of rainfall intensities on dew point temperature data at (a) daily, (b) hourly, and (c) 10-min resolution for the Netherlands, showing the 99.9 (magenta), 99 (blue), and 90th percentile (cyan). Dotted straight lines indicate the CC rate (black) and 2CC rate (red). The figures from top to bottom show the gradual change in scaling rates from the CC rate for daily precipitation to two times the CC rate for 10-min rainfall extremes. Note that for 10-min precipitation a very regular behavior is obtained for the highest percentile over a 20-degree dew point temperature range

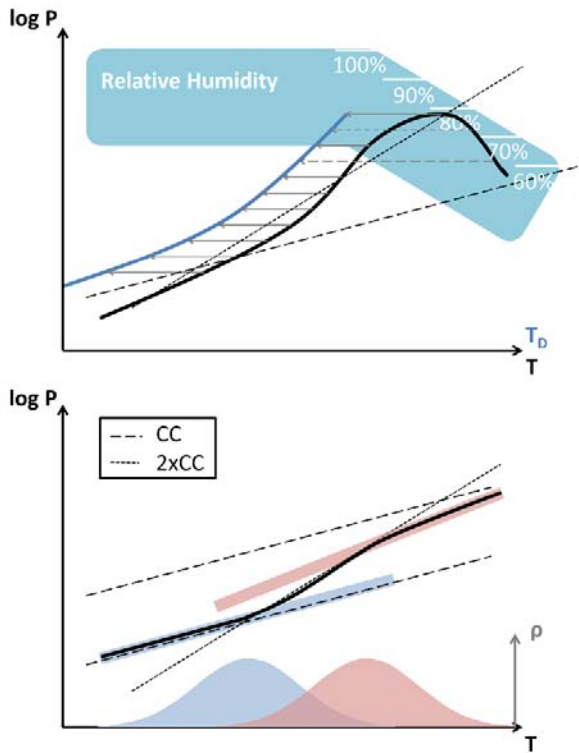


Figure 3: Schematic explaining the influence of accounting for humidity effects and rain types on the scaling of high percentile extreme rainfall. (a) Using dew point temperature (blue curve) instead of dry bulb (near surface) air temperature (black). When relative humidity is declining at higher temperatures, the dew point temperature is decreased more, indicated by (gray solid and dashed) arrows, such that the “hook shape” is reduced or disappears. (b) Considering large-scale stratiform precipitation (light blue) distributed across a lower temperature range, and convective precipitation (pink) across a higher temperature range, and different intensity and scaling (CC and super-CC, respectively) of each type. PDFs of the occurrence are shown as shaded surfaces for stratiform (light blue) and convective (pink) rainfall types. The combined scaling becomes much steeper in the transition between the two distributions, as indicated by the black curve.

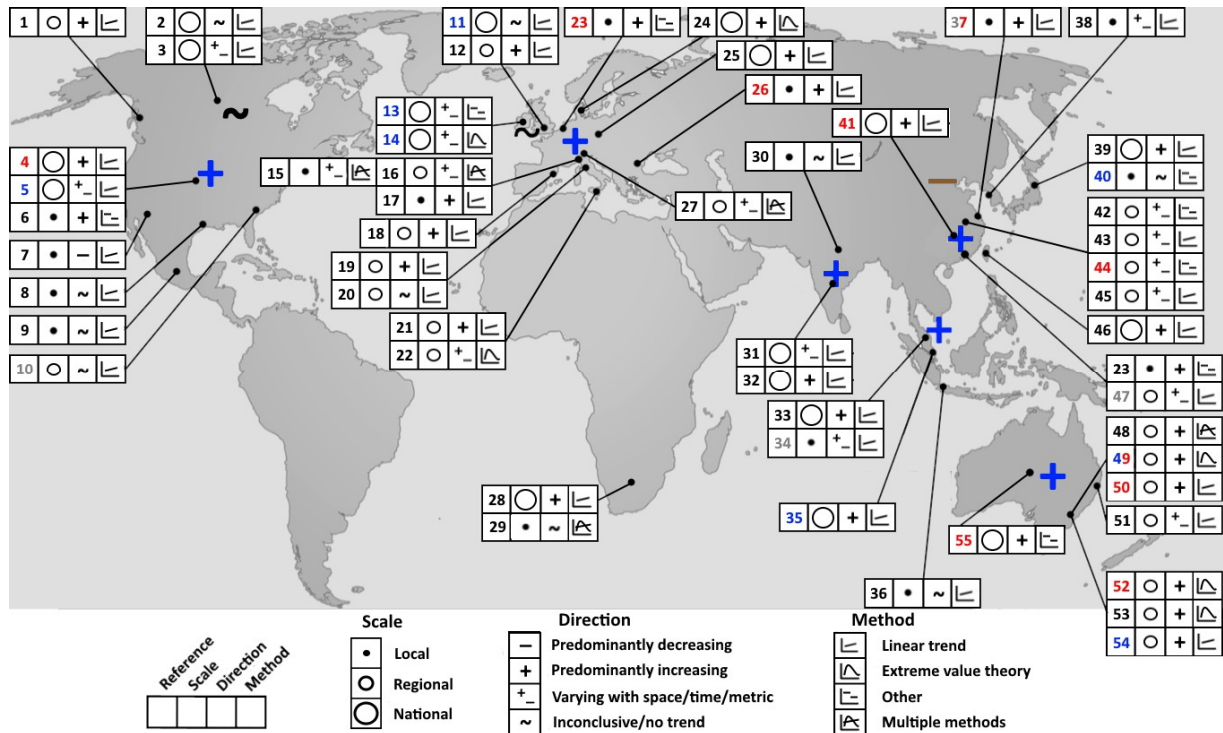


Figure 4: Summary of existing knowledge of observed changes in the frequency and/or intensity of sub-daily rainfall extremes. Information provided shows the spatial scale of each study, predominant direction of change, and methodology used. The direction of change includes analyses of different seasons, 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 Table S1 and associated references in the Supporting Information. These are color coded here to indicate if results are analyzed in the context of various drivers: temperature or temperature (CC) scaling (red), large-scale circulation (blue), or urbanization (grey).

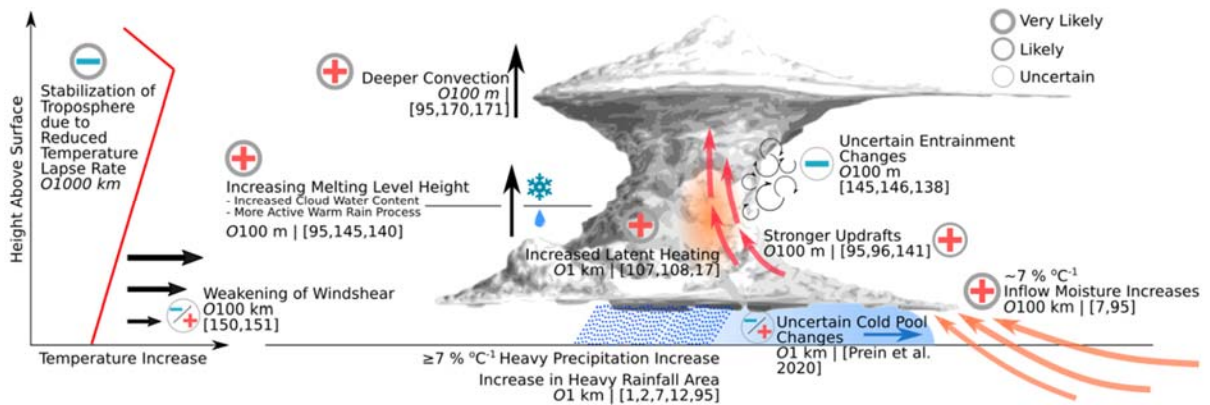


Figure 5: Climate change induced changes in extreme convective sub-daily precipitation processes. Plus/minus symbols indicate a positive/negative feedback regarding extreme precipitation intensity. The order of the characteristic spatial scale (O) is provided for each process and numbers in brackets indicate key references for each change. Uncertainties are indicated as the line thickness of circles around the feedback symbols with thin lines showing 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)

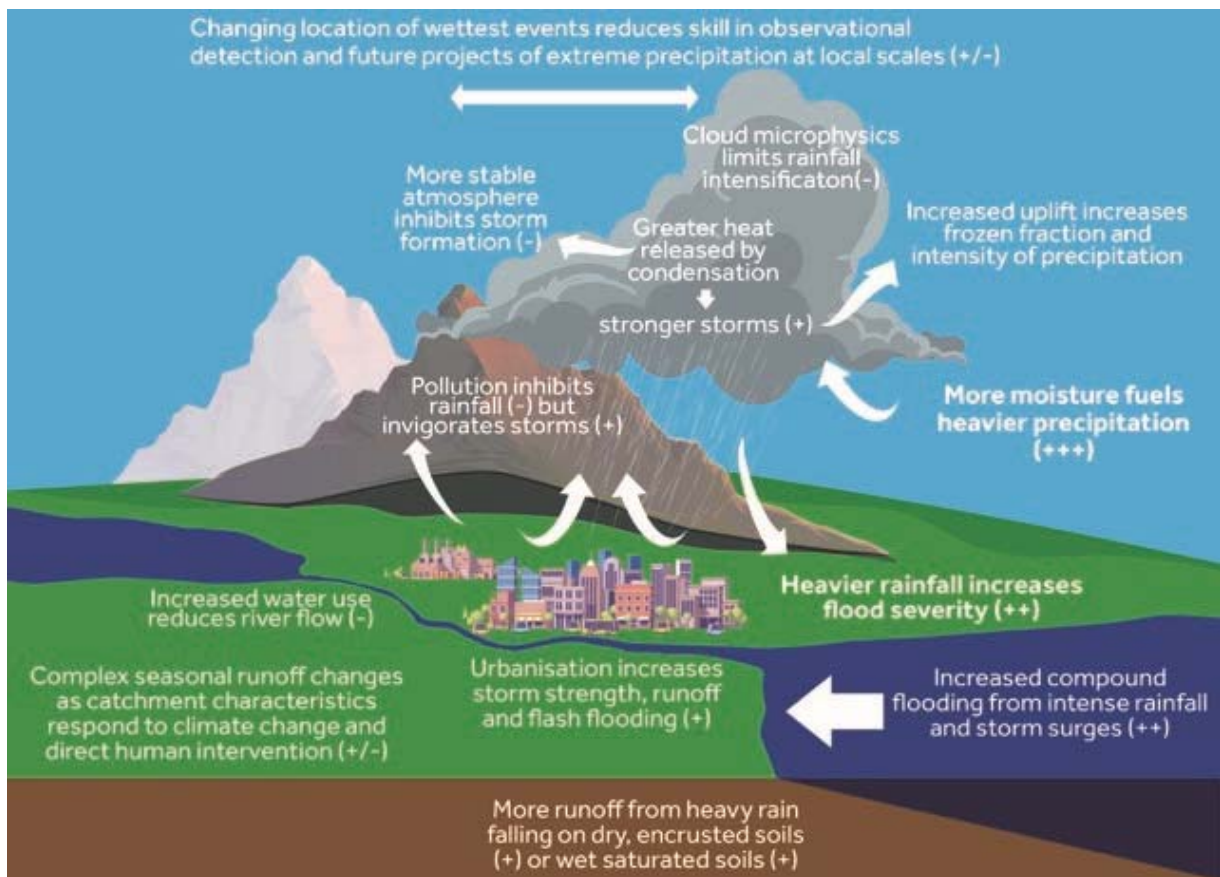


Figure 6: Schematic illustrating factors important in determining changes in sub-daily extreme precipitation and flooding (adapted from Figure 5 in ²¹⁸ to include processes specific to sub-daily precipitation extremes, with contributions to increases (+) and decreases (-) marked).

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Supporting Information

1	Burn et al. (2011)
2	Mekis et al. (2015)
3	Shephard et al. (2014)
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5	Yu et al. (2016)
6	Muschinski and Katz (2013)
7	Singer and Michaelides (2017)
8	Smith (2015)
9	Brown et al. (2019)
10	Ochoa et al. (2015)
11	Kendon et al. (2018)
12	Paulson (2010)
13	Kiely (1999)
14	Leahy and Kiely (2011)
15	Saidi et al. (2013)
16	Saidi et al. (2015)
17	Acquaotta et al., (2018)
18	Merino et al., (2018)
19	Vallebona et al. (2015)
20	Soldini and Darvini (2017)
21	Arnone et al. (2013)
22	Bonaccorso and Aronica (2016)

23	Lenderink et al. (2011)
24	Madsen et al. (2009)
25	Hanel et al. (2016)
26	Busuioc et al. (2017)
27	De Toffol et al. (2009)
28	Sen Roy and Rouault (2013)
29	Du Plessis and Burger (2015)
30	Kant (2018)
31	Sen Roy (2009)
32	Deshpande et al. (2012)
33	Syafrina et al. (2015)
34	Li et al. (2020)
35	Beck et al. (2015)
36	Siswanto et al. (2016)
37	Liang and Ding (2017)
38	Jun et al. (2019)
39	Fujibe et al. (2005)
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47	Wu et al. (2019)
48	Jakob et al. (2011)
49	Westra and Sisson (2011)
50	Chen et al. (2013a)
51	Laz et al. (2014)
52	Chen et al. (2013b)
53	Zheng et al. (2015)
54	Hajani et al. (2017)
55	Guerreiro et al. (2018)

Table S1: Corresponding references associated with studies of sub-daily rainfall trends shown in Figure 3. Numbers correspond to the reference index for each study.

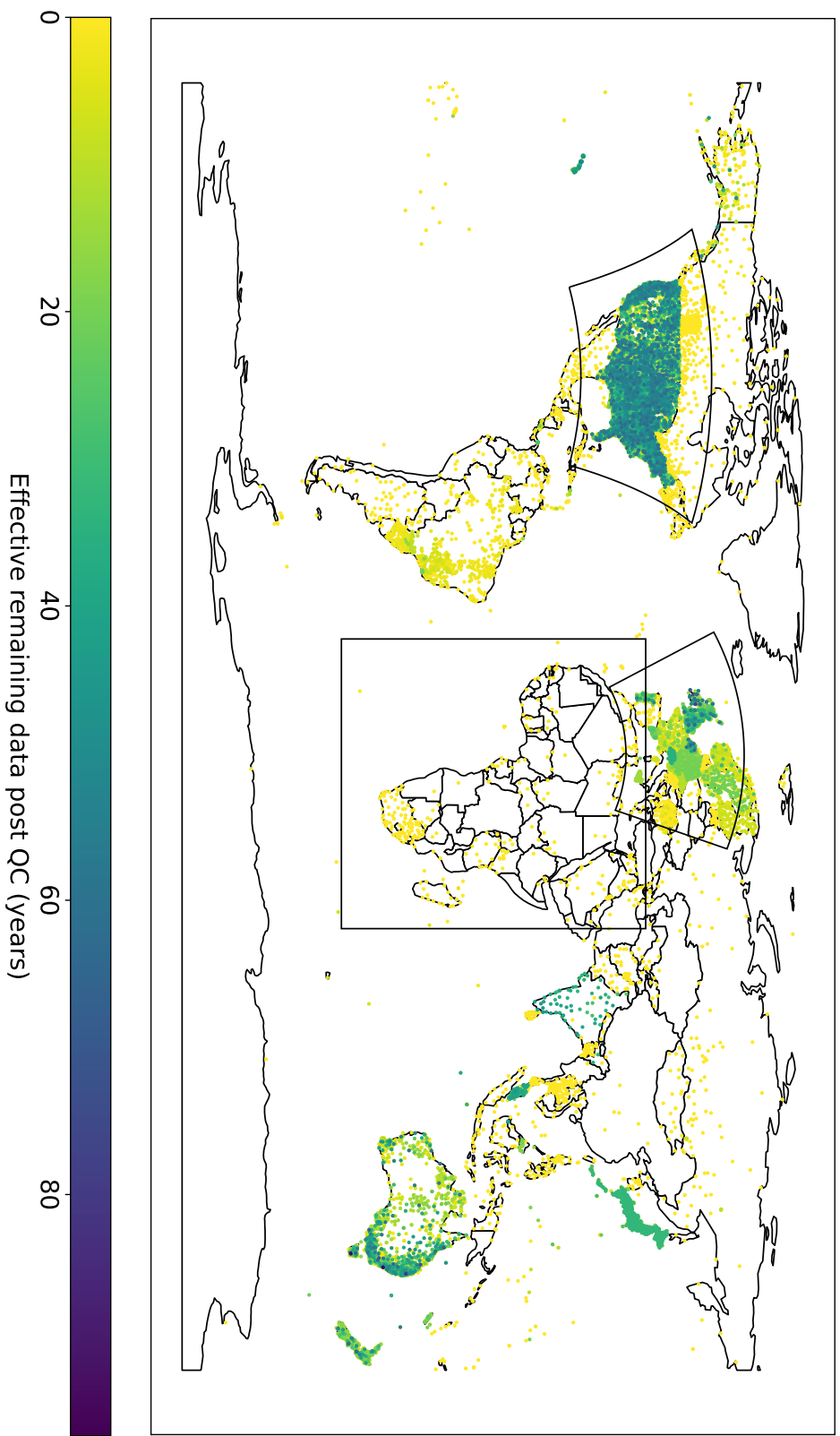
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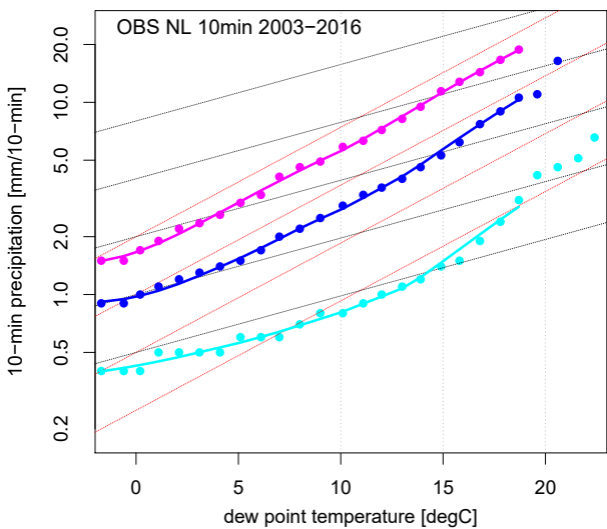
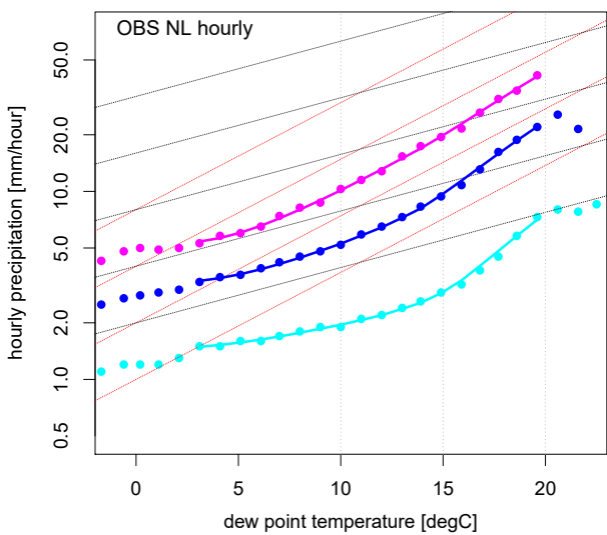
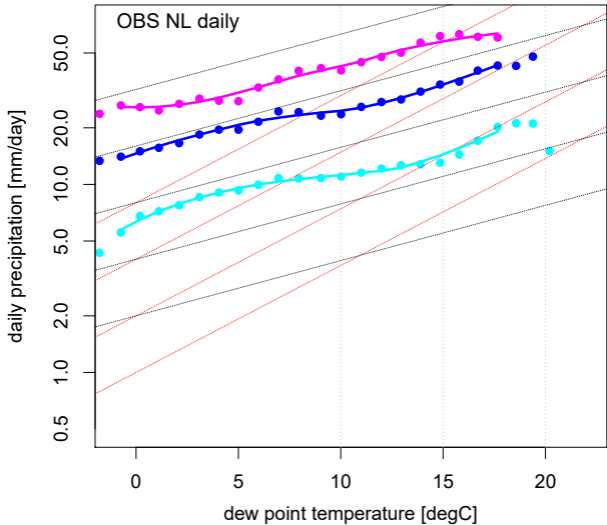
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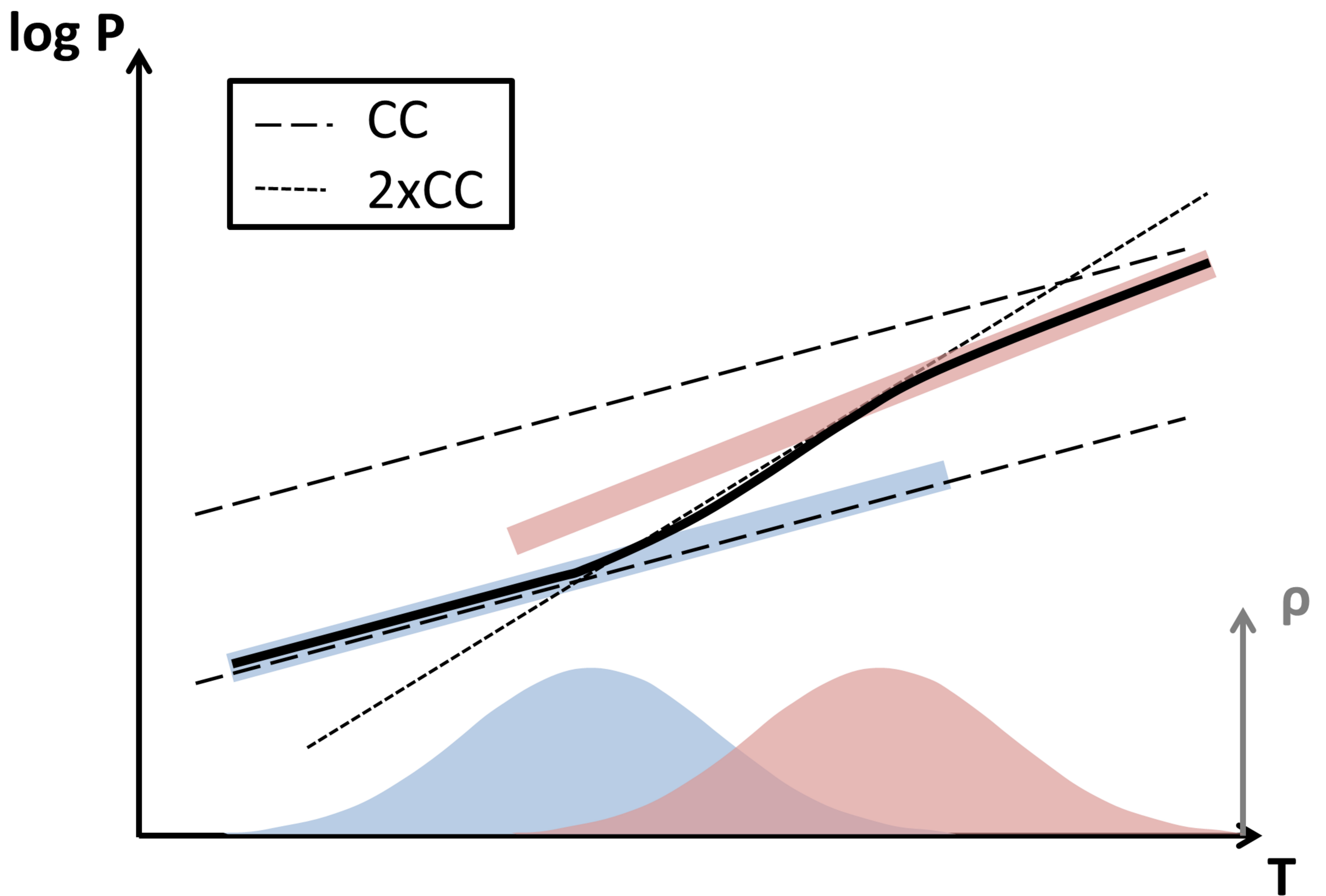
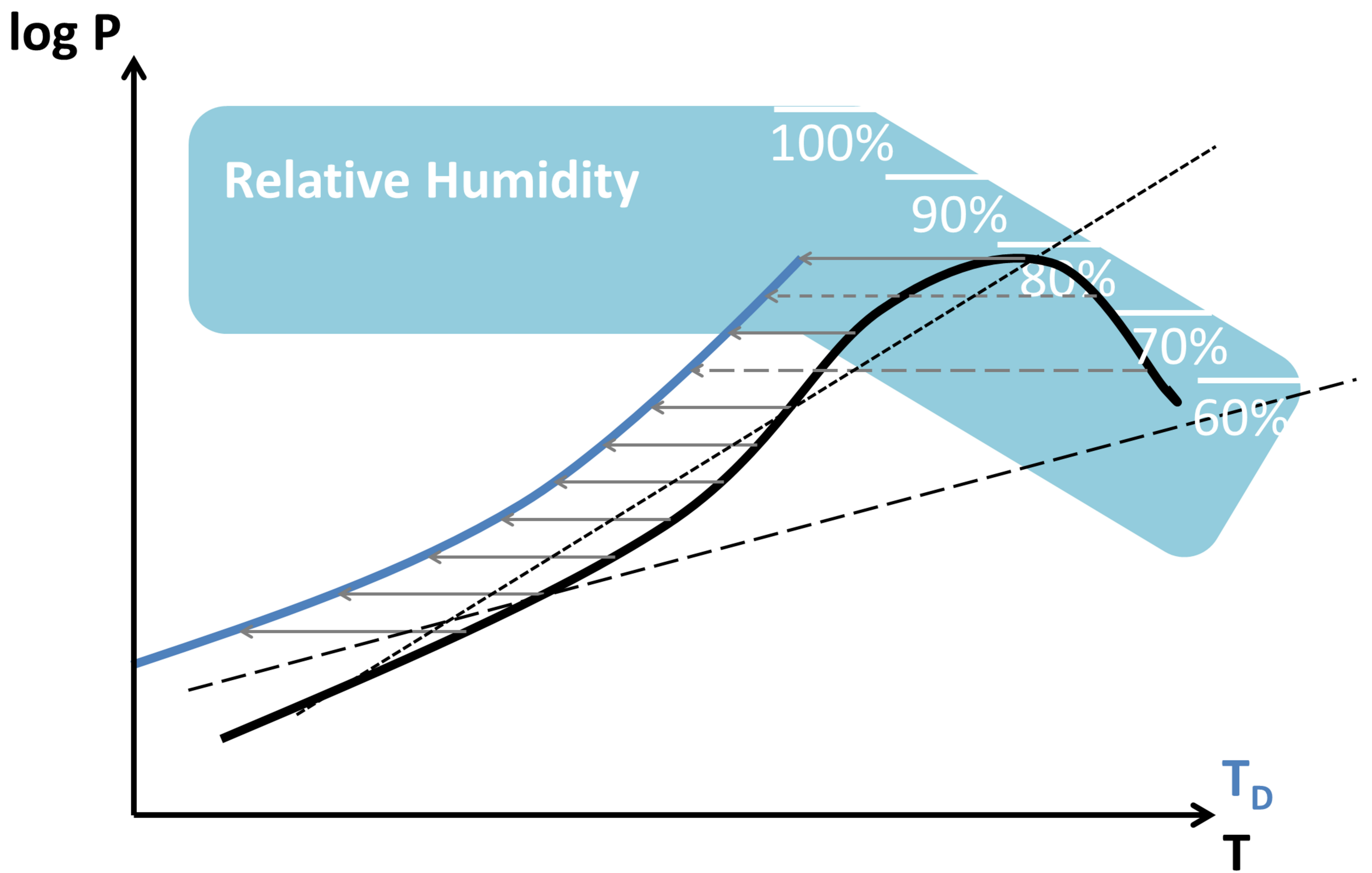
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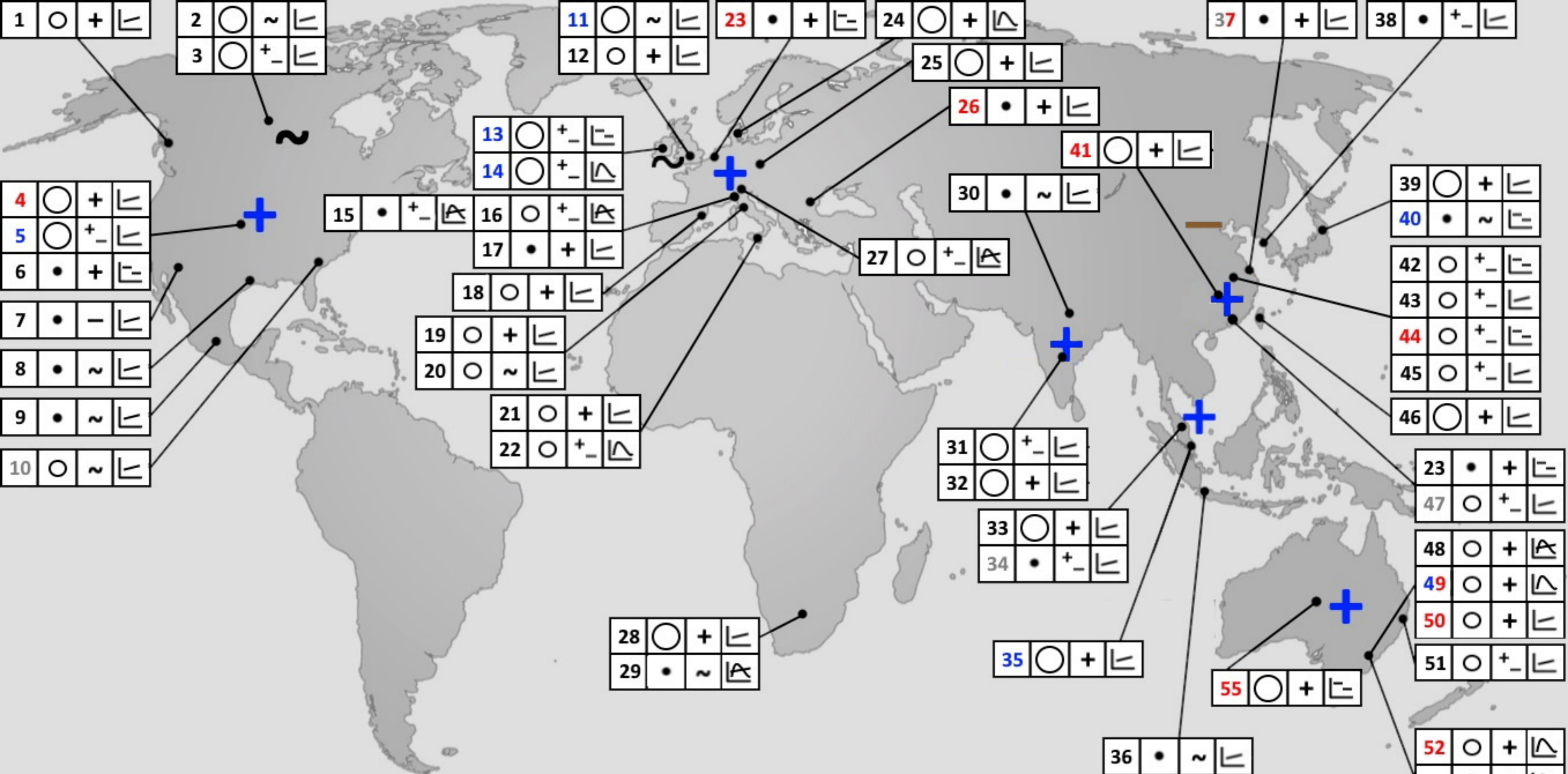
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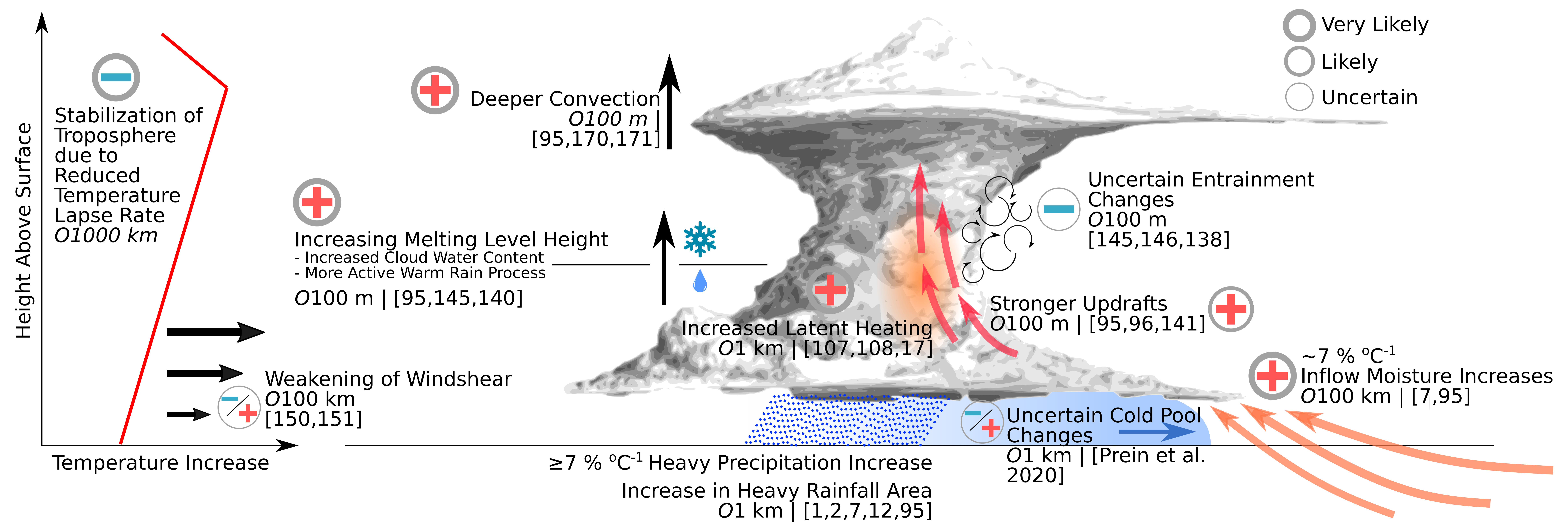
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Changing location of wettest events reduces skill in observational detection and future projects of extreme precipitation at local scales (+/-)

