State-of-the-Art Review

Climate Change and Rainfall Intensity–Duration–Frequency Curves: Overview of Science and Guidelines for Adaptation

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Abstract: One of the most important impacts of a future warmer climate is the projected increase in the frequency and intensity of extreme rainfall events. This increasing trend in extreme rainfall is seen in both the observational record and climate model projections. However, a thorough review of the recent scientific literature paints a complex picture in which the intensification of rainfall extremes depends on a multitude of factors. While some projected rainfall indices follow the Clausius-Clapeyron relationship scaling of an ~7% increase in rainfall per 1°C of warming, there is substantial evidence that this scaling depends on rainfall extremes frequency, with longer return period events seeing larger increases, leading to super Clausius-Clapeyron scaling in some cases. The intensification of extreme rainfall events is now well documented at the daily scale but is less clear at the subdaily scale. In recent years, climate model simulations at a finer spatial and temporal resolution, including convection-permitting models, have provided more reliable projections of subdaily rainfall. Recent analyses indicate that rainfall scaling may also increase as a function of duration, such that shorter-duration, longer return period events will likely see the largest rainfall increases in a warmer climate. This has broad implications on the design and the use of rainfall intensity–duration–frequency (IDF) curves, for which both an overall increase in magnitude and a steepening can now be predicted. This paper also presents an overview of measures that have been adopted by various governing bodies to adapt IDF curves to the changing climate. Current measures vary from multiplying historical design rainfall by a simple constant percentage to modulating correction factors based on return periods and to scaling them to the Clausius-Clapeyron relationship based on projected temperature increases. All of these current measures fail to recognize a possible super Clausius-Clapeyron scaling of extreme rainfall and, perhaps more importantly, the increasing scaling toward shorter-duration rainfall and the most extreme rainfall events that will significantly impact stormwater runoff in cities and in small rural catchments. This paper discusses the remaining scientific gaps and offers technical recommendations for practitioners on how to adapt IDF curves to improve climate resilience. **DOI: 10.1061/(ASCE)HE.1943-5584.0002122.**

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Introduction

The design of most hydraulic engineering infrastructures is based on local intensity–duration–frequency (IDF) curves, which provide extreme rainfall intensity (mm/h) values for various durations (minutes to days) and return periods (years). Typically, IDF curves cover rainstorm durations from 5 min to 24 h, with return periods from 2 to 100 years. These are normally sufficient to cover the needs of most applications dealing with streamflow, runoff routing, and floods and, therefore, help design infrastructures resilient to extreme rainfalls. Indeed, IDF curves are widely employed in stormwater management and engineering applications across the world (e.g., Akan 1993; Ferguson 1998; Seybert 2006).

IDF curves are best suited for hydrological studies in urban and small rural catchments. They can also be used for larger catchments with concentration times exceeding 24 h. However, when dealing with catchments in mountainous or cold areas, snowmelt and rain-on-snow events can become the driving processes that generate design flood events, requiring different methods such as continuous hydrological modeling and flood frequency analyses. This paper does not address such cases but focuses exclusively on rainfall-generated flood events, for which IDF curves are the main design tool.

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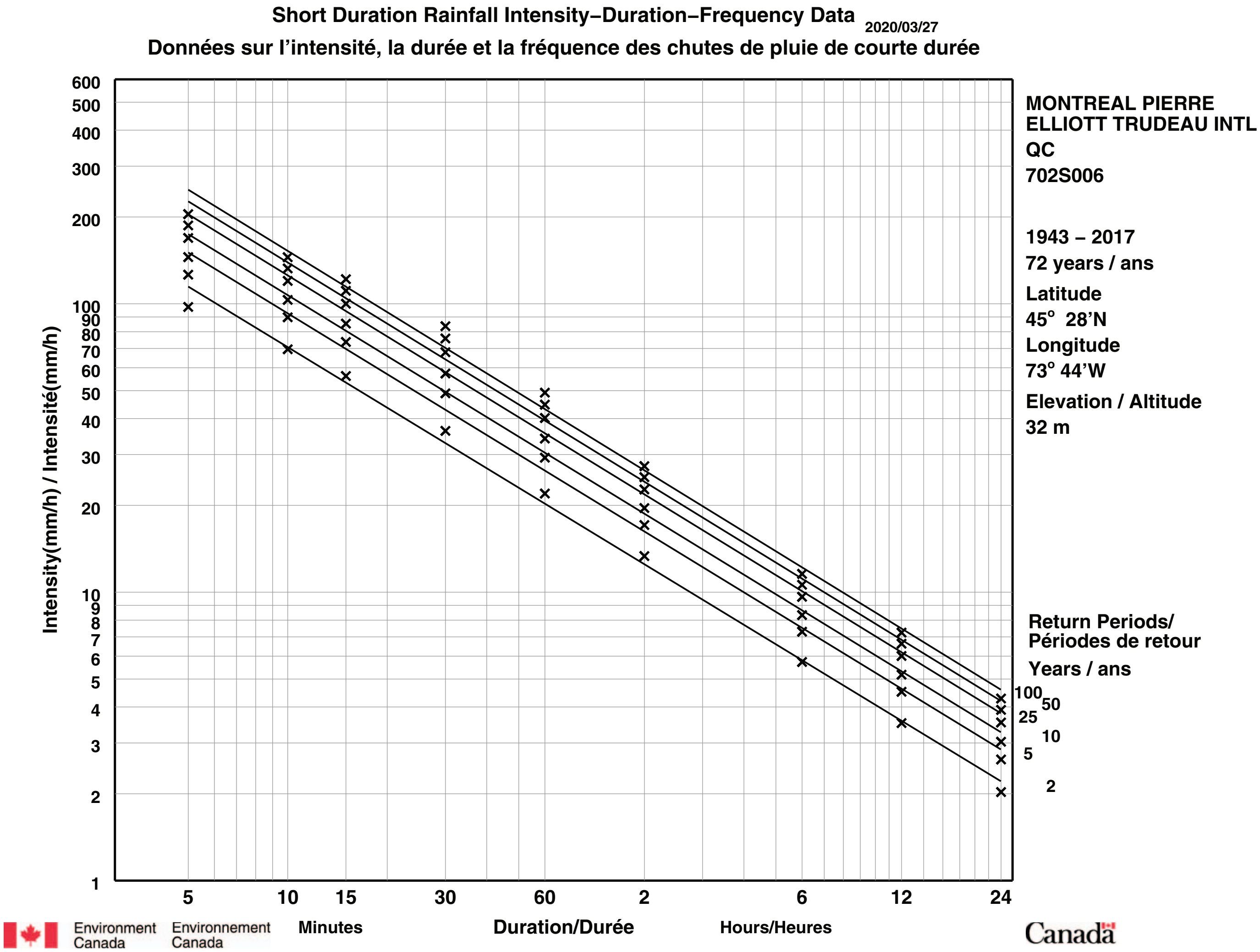

Fig. 1. (Color) Example of intensity-duration-frequency (IDF) curves from ECCC at Montreal Pierre-Elliott Trudeau International Airport (station 702S006). Log-transformed rainfall durations and intensities are shown on the abscissa and the ordinate, respectively. Different quantiles associated with return periods ranging from 2- to 100-year, fitted from a Gumbel distribution, are shown with the x’s. The lines represent the linear best fit over the log-transformed values. (Reprinted from Environment Canada © 2020.)

These curves are typically developed by using an extreme value distribution locally, which is fitted to historical annual maxima series of accumulated rainfall data of various durations. Most countries have their own governmental bodies or agencies responsible for producing IDF curves at the national level through standard procedures [e.g., Environment and Climate Change Canada (ECCC 2019) and the National Oceanic and Atmospheric Administration (NOAA) Atlas 14 in the United States (Perica et al. 2018)]. An example of IDF curves from ECCC is provided in Fig. 1.

Most IDF curves used operationally rely on a stationarity assumption, in which the climate remains stable over time. This implies a stationary spatial and temporal structure of rainfall (Cheng and AghaKouchak 2014; Myhre et al. 2019). This hypothesis has long been challenged, given the impact of low-frequency internal climate variability (natural variations in climate due to sea surfaces temperature anomalies, such as the Atlantic Multidecadal Oscillation and El Nino Southern Oscillation) on rainfall and temperature patterns (Milly et al. 2008; Ouarda et al. 2019). In addition, the intensity and frequency of extreme rainfalls are affected by the anthropogenic forcing resulting from greenhouse gas (GHG) emissions (Fadhel et al. 2017; Mamoon et al. 2019; Myhre et al. 2019). Indeed, robust increases in the magnitude of daily rainfall were identified in both observations and climate models over the last half of the 20th century (Min et al. 2011; Westra et al. 2013), with an expected intensification of rainfall extremes in the decades to come (Donat et al. 2016). There is also considerable evidence that short-duration (subdaily) rainfall extremes are becoming more intense, as highlighted by Westra et al. (2014) and Fowler et al. (2021a, b), resulting in increased flood risk (Fowler et al. 2021c). This increase in rainfall intensity will potentially lead to a reduction in water security, as water will not redistribute from the soil to the surface reservoirs, leading to plant water stress and issues in agriculture (Eekhout et al. 2018).

The observed and projected intensification of daily and subdaily extreme rainfall calls into question the applicability of historical IDF curves, which do not explicitly consider extreme rainfall nonstationarity, in designing infrastructure that will operate in future climate conditions. This is especially true for many engineering structures, which, for the most part, will still be in operation by the end of the 21st century (Arnbjerg-Nielsen 2012; Cheng and AghaKouchak 2014; Mailhot and Duchesne 2010; Yilmaz et al. 2014). For instance, Cheng and AghaKouchak (2014) suggest that a stationary climate assumption might lead to an underestimation of extreme rainfalls by as much as 60%, increasing flood risk and

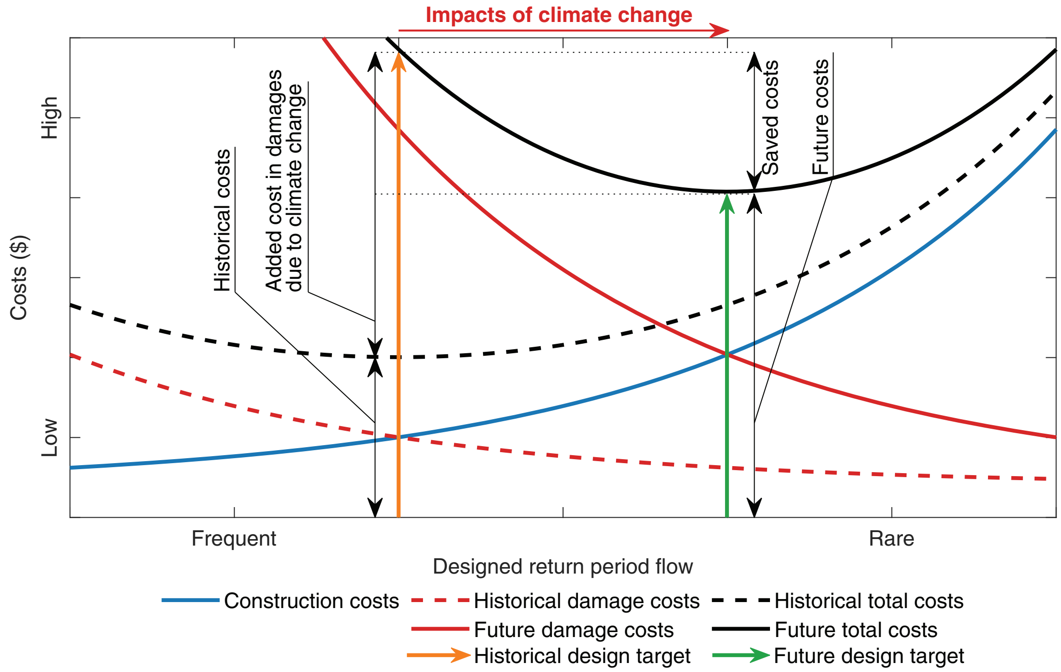

Fig. 2. (Color) Conceptualization of climate change impacts on the theoretical design compromise for typical urban infrastructure.

failure risk in infrastructure systems. We can affirm that most existing stormwater runoff infrastructures are ill-adapted, and design strategies, including climate change adaptation, need to be implemented (Lopez-Cantu and Samaras 2018; Myhre et al. 2019). IDF curves are a critical part of the design process and require updating to account for an evolving climate and reduce infrastructure vulnerability (ASCE 2018; Watt and Marsalek 2013; Yan et al. 2021).

Fig. 2 shows a typical conceptualization (Kind 2012; Merisalu et al. 2021) of the tradeoff between investment and risk that optimizes the total cost of infrastructure, such as stormwater drainage systems. Infrastructure design attempts to balance construction costs (solid blue curve) against damages if the designed return period flow is exceeded during the lifespan of the element (dashed red curve). There is a theoretical optimum of the total cost (dashed black curve) upon which the return period flow is selected, as shown by the orange arrow in the current climate.

The science (as reviewed in this work) shows, with a high level of certainty, that the projected increases in extreme rainfall lead to an increased likelihood of exceeding the return period design flow, therefore increasing the damage risk. This can be seen in Fig. 2, with the shift of the damage curve to the right (solid red curve), which in turn moves the optimal total cost to the right (green arrow). The theoretical cost of the underdesigned infrastructure element is outlined by the difference in height between the orange and green arrows. Thus, building climate-resilient infrastructure through a larger investment in the initial construction cost (blue curve) could ultimately lead to a lower total cost (black curve) over the lifespan of the infrastructure elements, considering their typical long service life. For stormwater drainage infrastructure, the challenge is to quantify the expected impacts of climate change on the red curve, in other words, the projected changes in IDF curves.

A simple illustration of the cost-benefit of adapting to climate change consists in oversizing a culvert by choosing a larger diameter to provide more conveyance. While this oversizing generates a larger initial cost (blue curve), the replacement of a whole section of a washed-away road following an extreme storm event (exceeding the culvert's design capacity) will be more expensive overall.

The importance of larger initial investments is clearly illustrated with the current state of most infrastructures in North America. For instance, the latest ASCEs' Infrastructure Report Card (ASCE 2017) gave the overall infrastructure of the United States a D+ rating (i.e., poor, at-risk). Similarly, the latest Canadian Infrastructure Report Card (CIRC 2019) underlines that about 30% of Canada's water infrastructure [e.g., drinking water, wastewater, stormwater, and, to some extent, roads (culverts), and bridges] is in very poor, poor, or fair conditions. A large part of existing infrastructures is so scheduled for renewal in the short term, and replacements are expected to have a lifespan of between 50 and 100 years. Climate change adaptation must therefore be incorporated in planning and designing new infrastructure projects in order to handle the upcoming increases in rainfall extremes during the projects' lifespan. This means that new infrastructure projects require investing more capital in the short term for future-proofing, which implies that difficult financial decisions will have to be made. However, the cost of not adapting to climate change is more expensive than the cost of adapting to climate change (Chambwera et al. 2014). This should compel stakeholders to integrate climate change considerations into water and infrastructure management (Wasko et al. 2021).

The aim of this study is threefold: (1) provide a critical review of recent studies on the evolutive trends of extreme rainfall under a warmer climate; (2) assess how these findings will influence the IDF curves in the future; and then (3) propose a nonstationarity model of IDF curves that is easily accessible for different regions of the world for design and operational purposes. An overview of the science on the expected impacts of climate change on rainfall extremes is provided in the next section. A discussion on current scientific gaps, current governmental agency guidelines, and new technical recommendations from an operational perspective is then presented, followed by a conclusion and our final remarks. The overarching motivation of this work is to introduce technological support for adaptation in the area of infrastructure design by providing key findings on how to adapt IDF curves in the context of climate change.

Overview of Science

Theoretical Background and Climate Modeling of Extreme Rainfall Events

Mechanisms Leading to Extreme Rainfall Events

Rainfall is the outcome of a long chain of physical processes, starting with the evaporation of water into the air as water vapor, which then condenses by binding to nucleation sites (such as dust particles and aerosols) when an air parcel rises to form clouds, from which rainfall ultimately falls under gravity (Trenberth et al. 2003). Three types of rainfall can be produced, depending on the different ways leading to the condensation of the atmospheric water vapor (Trenberth et al. 2003; Poujol et al. 2020, 2021). Firstly, orographic rainfall occurs when the air is forced to rise due to the presence of a mountain, leading to the condensation of water through adiabatic cooling, creating clouds and then periodic rainfall on the windward side of a mountain (Roe 2005). Secondly, stratiform rainfall originates from the rise of large air masses induced by weather fronts and is often associated with meteorological systems that move over long distances, producing long mild showers over large areas (Houze 1997). Thirdly, convective rainfall arises from the fast rise of a local air mass under a conditionally unstable atmosphere caused by local differential heating, leading to cumulonimbus clouds from which short and local heavy rainfalls are produced, sometimes in the form of hail (Houze 1997). An algorithm was recently proposed to separate these three types of rainfall in climate model simulations (Poujol et al. 2020). Many studies argue that the hydrological cycle is currently intensifying and will continue to intensify under global warming (Huntington 2006; Trenberth 2011), although this hypothesis is debated (Koutsoyiannis 2020). In a future warmer world, a larger amount of water vapor in the atmosphere could potentially lead to an increase in the three types of rainfall (Trenberth et al. 2003). Of the three forms, convective rainfall, which is responsible for most subdaily rainfall extremes, is expected to increase the most, according to a mechanism in which fewer (but larger) storms generating heavier rainfall events could take place in a warmer future (Dai et al. 2020).

Rainfall extremes occur in organized atmospheric phenomena, such as mesoscale convective systems (MCS) (Prein et al. 2017a), tropical and extratropical cyclones (Gutmann et al. 2018), atmospheric rivers (Huang et al. 2020), and squall lines (Purr et al. 2019), in which deep convection (characterized as an atmospheric parcel that is lifted above the 500 hPa pressure level) is central. According to the atmospheric scales of motion of these phenomena, only high-resolution climate models, such as those that are regional and convection-permitting, are capable of simulating these processes and simulating subdaily extremes comparable to observations (Fowler et al. 2021a).

Clausius-Clapeyron Relationship

The capacity of the atmosphere to contain water is governed by the Clausius-Clapeyron (CC) equation, according to which the saturation of specific humidity increases by a rate of 7% per degree Celsius of warming (Westra et al. 2014). Assuming constant relative humidity, an increase in temperature could lead to an increase in the water vapor available to generate rainfall, but the relation is not that straightforward. At the global scale, global climate models predict an increase in mean precipitation by approximately 2%–3% per degree Celsius of warming (Held and Soden 2006), which can be explained by global energy constraints (Allen and Ingram 2002). However, this limit is not uniform and depends on the geographical location, as well as on the rainfall duration and intensity. According to climate model projections, future changes in extreme rainfalls seem to follow and exceed the CC rate in certain cases, even in regions where the mean rainfall is projected to decrease (Aalbers et al. 2018; Prein et al. 2017b).

A warmer atmosphere can hold more moisture (~7%/°C), which can potentially lead to more rainfall. Many studies suggest that extreme rainfall may scale with the increasing precipitable water content as the atmosphere gets warmer (Drobinski et al. 2018). Subsequently, this scaling between extreme rainfall and temperature will be called rainfall scaling. However, this scaling of rainfall with respect to temperature seems to be sensitive to rainfall intensity. Analyses of observed time series from different weather stations indicate that daily rainfall extremes follow the CC rate (Fischer and Knutti 2016; Guerreiro et al. 2018; Westra et al. 2013), while hourly rainfall extremes seem to exceed this rate (i.e., the super CC rate; Berg et al. 2013; Lenderink and van Meijgaard 2008, 2010; Panthou et al. 2014; Westra et al. 2014).

The scaling of hourly rainfall extremes is sensitive to temperature. In the studies by Drobinski et al. (2018) and Prein et al. (2017b), super CC rates were found at low to moderate temperatures (around 10°C–20°C), but lower and negative scaling rates were found above approximately 20°C, likely due to a reduction in relative humidity at warmer temperatures. Interesting reviews of temperature scaling of extreme subdaily rainfalls are presented by Westra et al. (2014) and Fowler et al. (2021a). Scaling above the CC rate is locally possible with dynamical feedbacks involving convective processes, and different mechanisms have been proposed: cold pool collisions (Haerter et al. 2018; Moseley et al. 2016), intensification of updrafts in the cloud core (Loriaux et al. 2013), or moisture-driven increases in large-scale ascent (Nie et al. 2018). Although the scaling rate found in observations is sensitive to the methodology employed, and its translation to a warmer climate is disputed (Chan et al. 2016; Prein et al. 2017b; Zhang et al. 2017), the hypothesis according to which extreme subdaily rainfall events are expected to increase at the CC scaling rate (~7%/°C) and above for shorter-duration and longer return periods is generally accepted based on observations and climate modeling (Förster and Thiele 2020). This provides a few hints about how IDF curves should be adjusted in the future.

Ability of Climate Models to Simulate Extreme Rainfall

To reliably project the future evolution of IDF curves in a warmer climate, climate models must be able to simulate a wide range of rainfall extremes (2- to 100-year return periods) of different durations (5 min to 24 h) reasonably well. The ability of climate models to simulate rainfall extremes is dependent on their horizontal resolution, which determines the way convection is represented. Global climate models (GCMs) and regional climate models (RCMs) operating at resolutions equal to (or coarser than) 10 km have to use parameterizations to represent deep convection, which occurs on a scale of a few kilometers. The parameterization of convection, which is essential to represent subgrid-scale processes, is a well-known source of uncertainty in climate models, and it affects their ability to simulate rainfall extremes, especially at the subdaily scales (Berg et al. 2019; Kendon et al. 2012).

About 10 years ago, convection-permitting climate models (CPM) operating at horizontal resolutions ≤4 km emerged as powerful tools that considerably improved the simulation of shorter-duration (up to subhourly) rainfall extremes (Meredith et al. 2020; Vergara-Temprado et al. 2021; Meredith et al. 2021), with implications for water management (Orr et al. 2021). At such fine spatial resolutions, the deep convection, which is essential for a realistic simulation of rainfall extremes, is explicitly simulated, allowing one to switch off deep convection parameterization in CPMs (Ban et al. 2021). When compared with RCMs (with horizontal resolutions between 10 and 50 km), CPMs show significant added value for the simulation of rainfall extremes at the hourly scales (Luu et al. 2020), as well as the diurnal cycle of rainfall (Ban et al. 2014; Fumière et al. 2020; Lind et al. 2020). However, CPMs are relatively new models that are still considered to be in their infancy, which explains why they still suffer from several biases, such as their precipitation being too intense (Kendon et al. 2014) and being too dry and too warm over some continental regions (Berthou et al. 2020; Barlage et al. 2021). Many of these biases are currently addressed through active ongoing model developments that include calibration and the addition (or improvements) of some model components, including groundwater processes and turbulent schemes (Kendon et al. 2021). To eliminate these biases, bias correction is generally recommended, but the lack of reliable high-resolution (both spatially and temporally) gridded datasets restrains its wide use (Argüeso et al. 2013).

It is generally accepted that heavy daily rainfall (around the 95th percentile) is well simulated by global and regional climate models using horizontal resolutions coarser than 10 km (Iles et al. 2020), while subdaily and subhourly rainfall extremes are now well simulated with CPMs operating at resolutions ≤4 km (Lind et al. 2020; Meredith et al. 2020; Vergara-Temprado et al. 2021). Due to their high computational requirements, CPM climate simulations can only be computed over small regions of the globe, and only relatively short decadal simulations are possible, making the estimation of longer return periods only possible by extrapolating from fitted distributions (Cannon and Innocenti 2019).

In order to project future climate changes with climate models, two methods are currently adopted. The more common of these consists in comparing a climate simulation time window of typically 20 or 30 years forced by historical GHG concentrations with another one of the same length forced by a perturbed GHG concentration from a projected socioeconomic scenario. Thus, the future change often referred to as the climate change delta is associated with a specific GHG scenario forcing. Because climate models have different climate sensitivities and biases, an ensemble of climate models is needed to cover some of the sources of uncertainty. The downsides of this top-down method are that large ensembles of climate simulations are required to cover model uncertainty, and ensembles of simulations should be repeated for each socioeconomic scenario. Furthermore, this method also mixes the thermodynamics and dynamics aspects of climate change. The second method, the so-called pseudoglobal warming method (Schär et al. 1996), has recently been gaining interest in the atmospheric science community. It consists of perturbing the driving field (often a reanalysis) of an RCM by a certain factor, which is often taken from changes in temperature and humidity from an ensemble of GCMs (Prein et al. 2017b). Thus, the control RCM simulation can be compared with that forced with the perturbed driving field to assess changes related to that perturbation. This method has the advantage that the atmospheric circulation remains the same in the pseudofuture and that only the thermodynamic aspect of climate change is perturbed. Additionally, the method limits driving model biases in the case of a CPM being forced at its lateral boundary by biased global or regional climate models. However, future changes in the large-scale atmospheric circulation are not taken into account in this method, and the sequence of events is unchanged due to global warming [see the review by Adachi and Tomita (2020) for more details on the different methods, which can be adopted to constrain limited area models].

Projected Changes in Extreme Rainfall Events

A literature review of the projected changes in extreme rainfall events from climate models is provided in the following sections. This review focuses on the recent studies that have been conducted with the Representative Concentration Pathway (RCP) GHG emissions scenarios (IPCC 2013; Meinshausen et al. 2011). Considering the importance of the subdaily duration in the development of IDF curves, these more recent studies also took into account projections from higher spatiotemporal resolution climate models needed to investigate change over shorter durations (i.e., CPM and RCM simulations).

Daily Time Scale

Fischer et al. (2014) used 15 CMIP5 GCMs to analyze the forced response of heavy rainfall (Rx1day) changes. They found that disagreements between GCM projections of heavy rainfall primarily arise from internal variability and that the forced response of each GCM agrees remarkably well with one another. They estimated that changes in heavy rainfall at midlatitudes are robust among GCMs at about ∼7%/°C. Fischer and Knutti (2015) estimated that about 18% of the heavy daily rainfall (99.9th percentile, expected approximately once in every 3 years) is attributable to the observed temperature increase of 0.85°C, with this number moving to 40% for a 2°C of warming. For higher extremes, the percentage of attribution increases even more. Pfahl et al. (2017) decomposed the forced response of daily regional scale heavy rainfall (Rx1day) into thermodynamic and dynamic contributions. They showed that thermodynamics alone would lead to a spatially homogeneous increase of around 7%/°C, which is consistent across GCMs, while the dynamic contribution modifies the regional responses, amplifying their increase in the Asian monsoon region but weakening them in the Mediterranean and South African regions.

Bao et al. (2017) were able to accurately and robustly reproduce observed apparent scaling between heavy daily rainfalls and near-surface temperature with an ensemble of RCMs over Australia. Projections from the same RCMs show future heavy daily rainfalls that are increasing at higher rates than those inferred from the observed scaling, although the strongest rainfall events (99.9th percentile) scaled significantly faster at rates between 6% and 15%, depending on RCM configurations. Analyzing an ensemble of GCM projections according to water availability, Tabari (2020) found an intensification of extreme daily rainfall that increases as return periods become longer (less frequent), which converges asymptotically toward 6.5%/°C over all climatic regions. However, the author identified that this intensification increases with water availability from dry to wet regions and also with the seasonal cycle of water availability from summer to winter. The latter study emphasizes that updating the IDF curves will require considering water availability and will not be the same for all regions.

Kharin et al. (2013) investigated the change in the daily 20-year return period using a multimodel average over 29 CMIP5 models between the reference (1986–2005) and future (2071–2100) periods. Looking at the global median value over all land grid points, they found that the 20-year historical intensity corresponds to a 6-year event in the future, or roughly a 3- to 4-fold increase in frequency. Martel et al. (2020) obtained similar results for two GCM large ensembles of simulations when looking at the daily 20-year return period. For the 100-year event, they found that the historical intensity corresponds roughly to a 20-year event in the future or a five-fold increase in frequency.

Subdaily Time Scale

There is a general expectation that (very) short-duration rainfall extremes will become more intense in the next decades (e.g., Arnbjerg-Nielsen et al. 2015; Chandra et al. 2015; Fadhel et al. 2017; Forestieri et al. 2018; Khazaei 2021; Lima et al. 2016; Morrison et al. 2019; Moustakis et al. 2021), with an increase in frequency (Hosseinzadehtalaei et al. 2020; Myhre et al. 2019) and for longer return periods (Ganguli and Coulibaly 2019; Hosseinzadehtalaei et al. 2018; Martel et al. 2020; Ragno et al. 2018).

Berg et al. (2019) used a subset of the Euro-CORDEX 12 km RCM ensemble to evaluate and project the future evolution of hourly rainfall extremes. They highlighted that most RCMs underestimate the 10-year return period rainfall for durations of up to a few hours but performed better at longer durations (12 h). They also identified a strong relationship of extreme hourly rainfall changes with temperature across different subregions of Europe, emission scenarios, and future time periods, although the scaling varied considerably (1%–10%) between different combinations of GCMs and RCMs.

Berg et al. (2019) also highlighted the limitations in the ability of RCMs to simulate subdaily rainfall extremes, which are significantly improved in CPMs due to their explicit representation of deep convection (Ban et al. 2020; Ban et al. 2014; Kendon et al. 2012). An intensification of hourly rainfall extremes that are becoming progressively greater in intensity was revealed in many studies using CPMs over the UK (Fosser et al. 2020; Kendon et al. 2014), the Alps (Ban et al. 2020; Ban et al. 2015), Belgium (Vanden Broucke et al. 2019), Germany (Knist et al. 2020), Africa (Kendon et al. 2019), and Canada (Cannon and Innocenti 2019). Generally, the intensification is greater with CPMs than with RCMs, especially in the summer, when convection plays an important role in the production of rainfall extremes (Fosser et al. 2020; Kendon et al. 2017, 2014, 2019; Knist et al. 2020; Tabari et al. 2016; Vanden Broucke et al. 2019), a fact that was recently confirmed using an ensemble of 12 different CPMs in autumn but not in summer (Pichelli et al. 2021), although some studies found the opposite to be true (Ban et al. 2020, 2015).

In most studies, the simulated increase in intensification with CPMs stays below the CC rate (Ban et al. 2015; Hodnebrog et al. 2019; Vergara-Temprado et al. 2021). However, super CC rates were found in certain cases for the largest extremes (Fosser et al. 2020; Hodnebrog et al. 2019; Knist et al. 2020; Lenderink et al. 2021; Mantegna et al. 2017), in seasons other than summer (Ban et al. 2020), over Africa (Kendon et al. 2019), and for the shorter-duration extremes (Cannon and Innocenti 2019). Helsen et al. (2020) found small differences in the future increase in hourly rainfall between two different CPMs. They concluded that the future increase in hourly rainfall is more dependent on the region than on the CPMs. In addition, the scaling of the extreme rainfall intensification with temperature was revealed to be sensitive to the region (Hodnebrog et al. 2019; Prein et al. 2017b), to the topography (Helsen et al. 2020; Vanden Broucke et al. 2019), and to moisture availability (Prein et al. 2017b). Focusing on subhourly rainfall extremes, Vergara-Temprado et al. (2021) found an intensification of the extremes that grew with the intensity of the events but that remained below the CC rate, and that was slightly dependent on the rainfall durations over many European regions. Analyzing an ensemble of the same CPM over the UK, Fosser et al. (2020) found a stronger intensification, above the CC rate, of summer hourly rainfall with their CPMs compared to their driving 12 km ensemble. They revealed that the climate change signal of the extreme hourly rainfall intensification across their CPMs seemed to converge, likely because of the more realistic representation of local storm dynamics with CPMs. This fact led them to the conclusion that CPMs can potentially reduce the long-standing future extreme rainfall uncertainties associated with deep convection parameterization. Finally, recent studies using CPMs suggested that the urban heat islands of some megacities create a more unstable atmosphere, which increases vertical uplift and moisture convergence and, therefore, extreme rainfall intensity (Li et al. 2020) and frequency (Marelle et al. 2020).

Sources of Uncertainty

Uncertainties related to projected rainfall extremes are important, which ultimately translate into uncertain future IDF curves (Butcher and Zi 2019). The main sources of uncertainty are related to (1) the choice of the GHG emission scenario and the level of warming, (2) the difference in climate model parameters and structures, as well as the potentially critical issue of the underestimation of heavy-to-extreme rainfall events, (3) the internal climate variability (unforced variability due to the chaotic nature of the climate system), and (4) the downscaling and postprocessing of climate simulations.

GHG Emission Scenario

One of the largest sources of uncertainty, as we progress further into the 21st century, is the selection of a GHG emission scenario (Hawkins and Sutton 2011). The RCP8.5 scenario has been considered by many as the *business-as-usual* scenario reflecting a future with no effort in reducing GHG. Current emissions are close to the RCP8.5 scenario's projected emissions and are likely to remain so for at least the next decade. However, many scientists now argue that the RCP8.5 emissions projected by the end of the century are unlikely to happen as they would require unrealistic increases in fossil fuel use (Hausfather and Peters 2020). Nevertheless, a middle-of-the-road scenario such as the RCP4.5 is seen as too optimistic by many (Sanford et al. 2014; Schwalm et al. 2020). In short, the GHG emission scenario will remain a major source of uncertainty. Using the higher-emission scenarios is a conservative approach in dealing with this uncertainty.

Furthermore, the rate at which extreme rainfall increases does not directly depend on the emissions scenario (Pendergrass et al. 2015; Srivastav et al. 2014) but rather on the actual level of warming reached (Pendergrass et al. 2015; Seneviratne et al. 2016). Using a fixed level of global warming can be a way to circumvent the selection of a particular GHG emission scenario (Cannon et al. 2020; Seneviratne et al. 2016). However, knowing the time horizon at which a given threshold will be reached remains useful to engineers. For instance, some stormwater control measures can be designed with a relatively short lifespan of a few decades. In that case, a closer time horizon could be selected accordingly, also offering the potential for retrofitting at the end of the service life of the control measure.

Climate Models

Climate models such as GCMs and RCMs are not able to accurately simulate the magnitude and location of convective storms because of their coarse resolution (RCMs are typically coarser than ∼12 km) and constitute a large part of the uncertainty in designing IDF curves for the future climate, particularly for shorter rainfall durations (Hosseinzadehtalaei et al. 2018; Schardong and Simonovic 2019).

However, CPMs, through their finer spatial resolution (horizontal grid spacing <4 km), can improve the representation of subdaily rainfall both in intensity and duration at the regional to local scale (Ban et al. 2015; Kendon et al. 2014; Prein et al. 2015), therefore providing additional confidence in future IDF curves derived from CPMs (Cannon and Innocenti 2019; Mantegna et al. 2017). This has important implications for the building and infrastructure sectors (Kendon et al. 2017).

Internal Climate Variability

Many studies have shown that internal variability can mask the short- and long-term climate change signal for rainfall projections at both local and regional scales (Aalbers et al. 2018; Deser et al. 2012; Donat et al. 2020; Sanderson et al. 2018; Thompson et al. 2015). This variability becomes an important contributor to the uncertainty of the change in extreme rainfall due to warming, explaining about 20% of the intermodel spread in extreme rainfall change over extratropical land (Pendergrass et al. 2015). At the local scale, internal climate variability will dominate extreme rainfall uncertainty up to the end of the century in many parts of the world (Martel et al. 2018). For instance, the intensification of rainfall extremes can be distinctly different between two realizations of the same climate model at the regional scale (Aalbers et al. 2018; Fischer et al. 2014).

To account for internal variability and to quantify the epistemic uncertainty of the model structure in future extreme rainfall changes, it is recommended to use multimember ensembles (one climate model with several realizations that differ by their initial conditions) as well as multimodel ensembles (different GCMs with different RCMs) (Berg et al. 2019; Mailhot et al. 2007). Poschlod et al. (2021) suggest that a convection-permitting, single-model, initial-condition large ensemble would be a very valuable tool to improve the analysis of extreme rainfall and its natural variability.

From an operational point of view, engineering design has a long history of using methods based on the statistical theory of extreme value to extrapolate large return periods (e.g., 50- and 100-year events) from relatively short observation records (e.g., <30 years of data), leading to significant epistemic uncertainty (Ball et al. 2019; Katz 2013; Schulz and Bernhardt 2016). Single realizations from climate models are subject to a similar level of uncertainty, considering the 20- or 30-year time windows used to ensure stationarity over a given future time horizon (Aalbers et al. 2018). Large ensembles of climate simulations generated from the same climate model and external forcing provide a larger sample, allowing longer empirical annual maximum series (e.g., 50 simulations $\times$ 20 years $=$ 1,000-year annual maximum series), reducing the epistemic uncertainty (Martel et al. 2020). These large ensembles of climate simulations have recently been gaining in popularity both with RCMs (e.g., Aalbers et al. 2018; Leduc et al. 2019; Mizuta et al. 2017) and GCMs (Deser et al. 2012; Kay et al. 2015; Sigmond and Fyfe 2016), providing more robust (i.e., lower epistemic uncertainty) projected changes for rare rainfall extreme events.

Downscaling and Postprocessing

The scale dependence of rainfall extremes associated with the coarse resolution of climate models (GCMs and even RCMs) limits the use of raw simulations to analyze changes in subdaily rainfall extremes at the local scale (or at a site-specific scale, such as for urban infrastructure). By extension, the investigation regarding the changes to IDF curves is limited by the ability of climate models to simulate such shorter-duration rainfall extremes and their changes that will be introduced by climate change. GCMs (and even RCMs and CPMs) have specific model biases that must be considered and often removed in impact studies. As a result, an analysis of changes in local rainfall extremes often requires statistical postprocessing of climate simulations. Statistical postprocessing is widely used to develop projections of rainfall extremes at the regional and local scale (Fluixá-Sanmartín et al. 2019; Hosseinzadehtalaei et al. 2020; Khazaei 2021; Ning et al. 2015; Schoof and Robeson 2016). However, Fadhel et al. (2017) found that the uncertainty in the projected rainfall change compared to the rainfall in the current climate varies according to the selected reference period for the statistical postprocessing. This aspect of the uncertainty of benchmarking periods in postprocessing future rainfall projections is largely ignored by the engineering community. Already, CPMs provide improved estimates of extreme subdaily rainfall that are likely to further improve in the near future, and hopefully, the postprocessing step will soon become unnecessary in some cases.

Discussion

This discussion begins with a summary of the current knowledge on rainfall extremes based on a recent literature review, followed by an analysis of current guidelines to adapt the IDF curves under a warmer climate. Afterward, some adapted guidelines for practitioners and stakeholders are suggested to fill the scientific gap in the existing resources. Finally, key concerns regarding the detection of the climate change signal and its limitations for decision-making are provided.

What We Know

Since the 1950s, extreme rainfall events have become more intense and more frequent in many regions of the world (Westra et al. 2013, 2014). Scientists expect this trend in rainfall extremes to continue with global warming due to the association with the CC relationship (Li et al. 2021), leading to heavier rainfall events.

However, caution is required when applying the ~7%/°C rate regionally because there is some evidence of an increase in the CC rate for shorter-duration (hourly or subdaily) extremes when the temperature is in the range of approximately 12°C–22°C. Cases of super CC scaling are noted in North America (e.g., Nie et al. 2018), Europe (e.g., Lenderink et al. 2017; Wood and Ludwig 2020), and Australia (e.g., Bao et al. 2017; Mantegna et al. 2017). This is partly attributable to (1) an increase in the likelihood of convective versus stratiform rainfall occurrence as the temperature increases and (2) to the properties of convective rainfall itself (Westra et al. 2014).

There is also evidence of a limitation to the rate of increase (even a decrease) in rainfall intensities with increasing temperatures above ~24°C in some regions (Ghausi and Ghosh 2020; Pendergrass 2018). This appears to be associated with a decrease in moisture availability at high temperatures, even though the mechanism(s) leading to the moisture deficits are not fully understood to date (Westra et al. 2014).

There is an overwhelming consensus that extreme rainfall will intensify at the global and regional scales (e.g., Collins et al. 2013; Field et al. 2012; IPCC 2013; Kendon et al. 2019; Martel et al. 2020; Sillmann et al. 2013). The occurrence of extreme rainfall events in many regions (particularly in Europe and North America) has contributed to an increase in the number of related studies over the last few years [Fig. 3(a)]. These studies aim to assess projected changes in rainfall extremes better and to understand better the driving processes (e.g., Innocenti et al. 2019; Kirchmeier-Young and Zhang 2020; Myhre et al. 2019; Wood and Ludwig 2020). Many international initiatives have also emerged to improve the understanding regarding the relationships between global warming, atmospheric circulation, and extreme rainfall events, such as the INTElligent use of climate models for adaptatioN to nonStationary hydrological Extremes (INTENSE) project (Blenkinsop et al. 2018).

As discussed previously, many studies have projected increases in extreme rainfall statistics for the coming decades

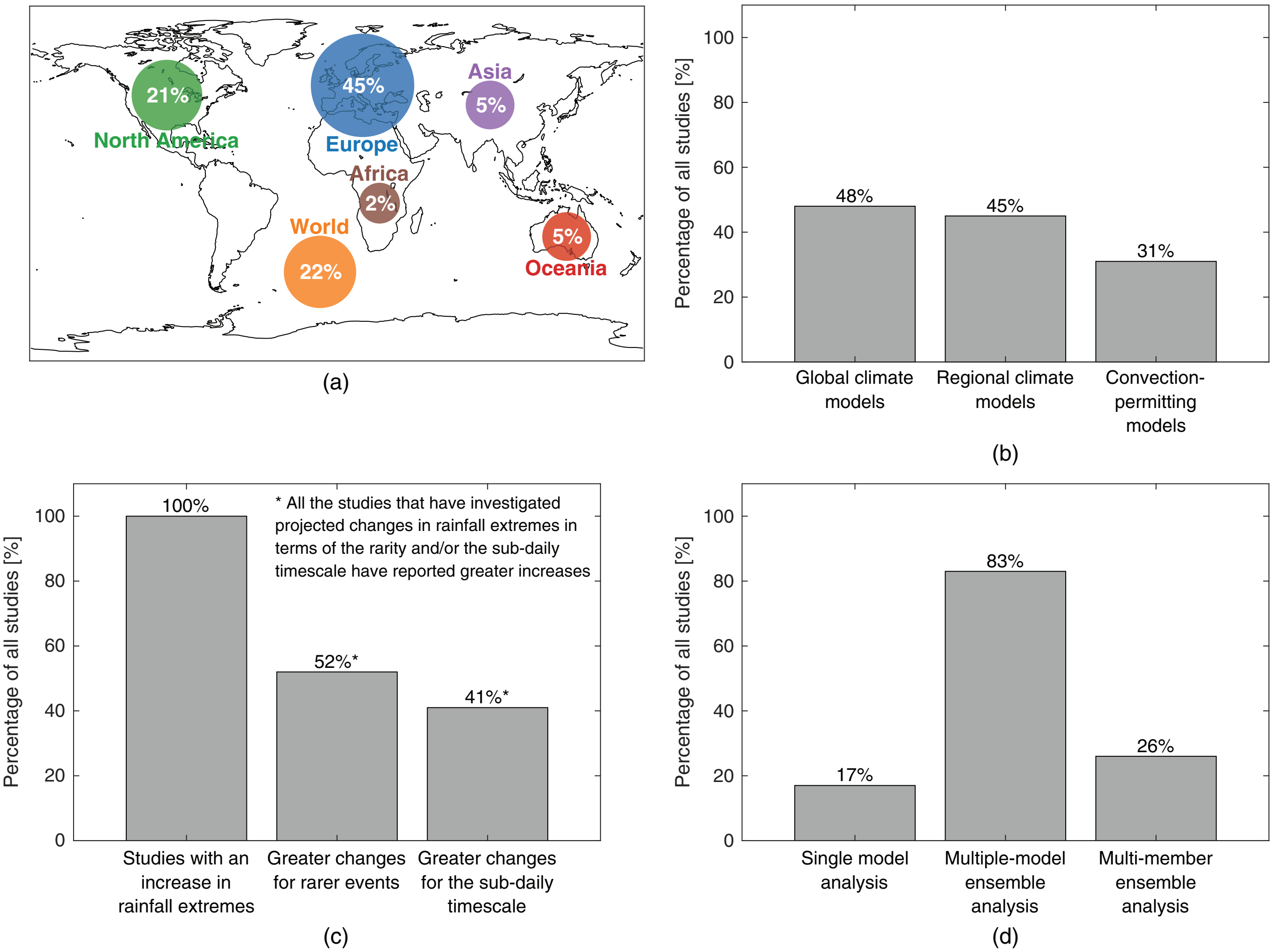

Fig. 3. (Color) Synthesis of 58 selected studies on rainfall extremes under climate change: (a) location of interest of the extreme rainfall studies investigated by region; (b) types of climate models (GCM, RCM, or CPM) used in the studies; (c) percentage of studies showing an increase in rainfall extremes; and (d) sampling of climate simulations used for the analysis (single model, multimodel ensemble, and multimember ensemble).

(Table S1), with an increasing trend correlated with the frequency of occurrence, as well as with the occurrence of the shortest-duration rainfall events [Fig. 3(c)]. A large number of the referenced studies are primarily based on GCM and RCM simulations [Fig. 3(b)] and on the use of more than one climate model [83%; Fig. 3(d)]; however, only a few integrate a multimember ensemble of the same climate model [26%; Fig. 3(d)]. Greater changes in rainfall extremes are projected for the subdaily timescale than for the daily timescale, especially for shorter durations [Fig. 3(b)] (Cannon and Innocenti 2019; Forestieri et al. 2018; Fowler et al. 2021a; Huo et al. 2021; Martel et al. 2020; Rajczak and Schär 2017; Westra et al. 2014; Wood and Ludwig 2020). More significant changes are projected in rare extreme rainfall events when compared to the common rainfall extreme indices, such as the daily annual maximum rainfall (Rx1day) [Fig. 3(b)] (Butcher and Zi 2019; Cannon and Innocenti 2019; Hosseinzadehtalaei et al. 2020; Huo et al. 2021; Kharin et al. 2018; Li et al. 2021). In particular, the 20-year daily rainfall event is projected to become 3–4 times more frequent (Kharin et al. 2013; Martel et al. 2020), while the 100-year daily rainfall event will be between 4 and 5 times more frequent (Martel et al. 2020), indicating a stronger amplification of rainfall extremes over longer return periods.

Analysis of Current Guidelines for Adaptation

The need to adapt IDF curves is now well recognized by many organizations. For example, the guidelines for Canadian water resources practitioners (CSA 2019) highlight the necessity to update the IDF curves more frequently than in the past because climate change is expected to induce an increased intensity and frequency of rainfall extremes in most areas over the next decades.

However, a more frequent update of IDF curves only accounts for changes over the recent past and does not cover the projected future changes in rainfall intensity. The uncertainties around the projected future climate are the main reason why projected changes in rainfall extremes are not included in IDF curves. The following subsections give local, regional, and national examples of guidelines, as well as standards for the modification of IDF curves to account for the future climate. Although these adaptation strategies might be imperfect (based on the current state of scientific knowledge previously discussed), they constitute an interesting step as they cover the lifespan of new infrastructure while improving its resilience.

Simple Constant Percentage Increase

The simplest adaptation strategy is the constant percentage increase, in which the same safety factor is used for all extreme rainfall design values. This method is currently used by some countries and regions. For instance, Belgium and the United Kingdom respectively apply an increase of 30% (Madsen et al. 2014; Willems 2011) and 20% (UK Department for Infrastructure 2020) on all rainfall extremes. Similar factors are also enforced by Canada's provincial governmental bodies, such as in the Province of Quebec (18%; MDDELCC 2017) and in the City of Moncton, New Brunswick (20%; EPWDR 2011).

Adaptive Percentage Increase

The adaptive percentage increase approach recognizes that future increases in rainfall extremes are not uniform and depend on various factors, such as temperature increases (as represented by future time horizons) and rainfall frequency. Different adaptive percentage increase strategies have been identified in different countries. One strategy that is used at the national level by Denmark for rainfall design (Arnbjerg-Nielsen 2008; Gregersen et al. 2014) is to implement different safety factors based on the frequency of the event selected in the design (i.e., 20%, 30%, and 40% increases are added to the 2-, 10-, and 100-year return periods, respectively). The Swedish Water and Wastewater Association (Madsen et al. 2014; Svenskt Vatten 2011) recommends a fixed percentage increase, with an adaptive variation between 5% and 30%, depending on the region. The UK Department for Infrastructure (2020) has selected a unique factor of 20% at the national level with incremental safety factors for rainfall design across all of England based on the time horizon (i.e., up to 10%, 20%, and 40% by 2040, 2070, and 2115, respectively; Defra 2020).

Percentage Increases Based on the Clausius-Clapeyron Relationship

The third approach is to apply a percentage increase based on the projected increase in warming. This follows the rationale behind the Clausius-Clapeyron relationship by providing correction factors based on the most likely local or regional increase in temperature. The future rainfall intensity can be computed as Eq. (1)

$$I_{fut} = I_{ref} \times \left[\frac{100 + R_{sc}}{100}\right]^{\Delta T} \quad (1)$$

where I_{ref} and I_{fut} = reference and future rainfall intensities, respectively; R_{sc} = rainfall scaling factor (%) based on the CC relationship; and ΔT = projected change in local temperature. The Australian Rainfall-Runoff guidelines (ARR; Ball et al. 2019) recommends a 5% increase per degree Celsius of warming while the Canadian Standard Association (CSA 2019) recommends a value of ~7%/°C. However, CSA (2019) acknowledges that shorter-duration events could follow a super CC relationship, implying that a larger rate than ~7%/°C of warming may be applied, depending on the area. This is also supported by multiple studies, as previously discussed.

Future IDF Curves

Some cities (e.g., NYC 2017; City of Vancouver 2018) or regions [e.g., Ontario (MTO 2016) and Newfoundland and Labrador (Finnis and Daraio 2018) in Canada] have already adopted future IDF curves for different time horizons (e.g., 2040 and 2070). The future IDF curves are usually an updated version of historical curves (obtained through standard methods) but upscaled based on the increase in rainfall extremes projected by the climate models. While it allows providing an adaptive percentage increase for both of the different durations and return periods, this approach often relies on GCM spatio-temporal resolutions, which are too coarse to produce reliable regional IDF curves.

Many studies attempt to provide regional future IDF curves by using either GCM [e.g., Canada (Srivastav et al. 2014); India (Chandra et al. 2015); Iran (Khazaei 2021); and the United States (Butcher and Zi 2019; Ragno et al. 2018)], or RCM/CPM [Australia (Mantegna et al. 2017); Belgium (Hosseinzadehtalaei et al. 2018); Canada (Ganguli and Coulibaly 2019); England (Fadhel et al. 2017); Italy (Forestieri et al. 2018); South Korea (Lima et al. 2016); and Spain (Fluixá-Sanmartín et al. 2019)] simulations. However, these future IDF curves are rarely adopted by governmental agencies and remain unused by practitioners.

Overall, most of the currently adopted guidelines fail to recognize the larger projected increases in extreme rainfall toward shorter and less frequent events. Climate model outputs can be used to explore rainfall characteristics/statistics; CPMs are particularly suited to investigate subdaily and subhourly extreme rainfall events. Furthermore, it is recommended to use multimember ensembles of climate models to reduce uncertainty (i.e., climate models and internal variability) in the projected values of rainfall extremes.

Suggested Adapted Guidelines for Practice

First, IDF curves based on past observations should be computed using the latest historical records. IDF curves are often decades-old [e.g., see the ECCC (2019) and NOAA's Atlas 14 (Bonnin et al. 2006)], and so do not even account for recent climate trends. Multiple guidelines thoroughly explain how to perform a rainfall frequency analysis from historical records to produce IDF curves (e.g., CSA 2019). Practitioners thus have some resources at their disposal to ensure that the IDF curves they use are up to date (e.g., less than 2 years old could serve as a general rule of thumb) before using them in any new design applications.

Then, for IDF curves covering the future climate, it is necessary to account for the intensification of rainfall extremes of shorter duration and of longer return periods. From our literature review, we found that the approach based on the CC relationship has strong potential but requires some modifications to integrate the expectation of intensification of projected rainfall extremes with frequency (as the return period increases) and with shorter durations (subdaily). Therefore, we propose to adapt Eq. (1) as follows

$$I_{fut,D,T} = I_{ref,D,T} \times F_T \times F_D \times \left(\frac{100 + R_{sc,24,2}}{100}\right)^{\Delta T} \quad (2)$$

where $I_{fut,D,T}$ = projected future rainfall intensity of duration D and return period T; $I_{ref,D,T}$ = reference period rainfall intensity of duration D and return period T; F_T = adjustment factor for return period $T (T > 2 \text{ years}, F_T \geq 1)$; F_D = adjustment factor for duration D shorter than 24 h $(D < 24 \text{ h}, F_D \geq 1)$; $R_{sc24,2}$ = rainfall scaling (%/°C) for the 24-h 2-year return period rainfall event; and ΔT = projected change in seasonal mean temperature (°C).

This equation is based on the expected rainfall scaling (%/°C) of the 24-h 2-year return period rainfall ($R_{sc,24,2}$), which has the smallest intensity in typical IDF curves. This value is equal to the median Rx1day value, which is one of the most common extreme rainfall indices studied in climate science (Table S1). Local Rx1day values can be computed easily and reliably using climate model outputs.

Because Rx1day is generally well represented in GCMs (Alexander and Arblaster 2017), we computed worldwide $R_{sc,24,2}$ factors based on 26 CMIP5 GCM simulations (see Table S2 for the list of GCMs used). Only the first member (r1i1p1) of each GCM

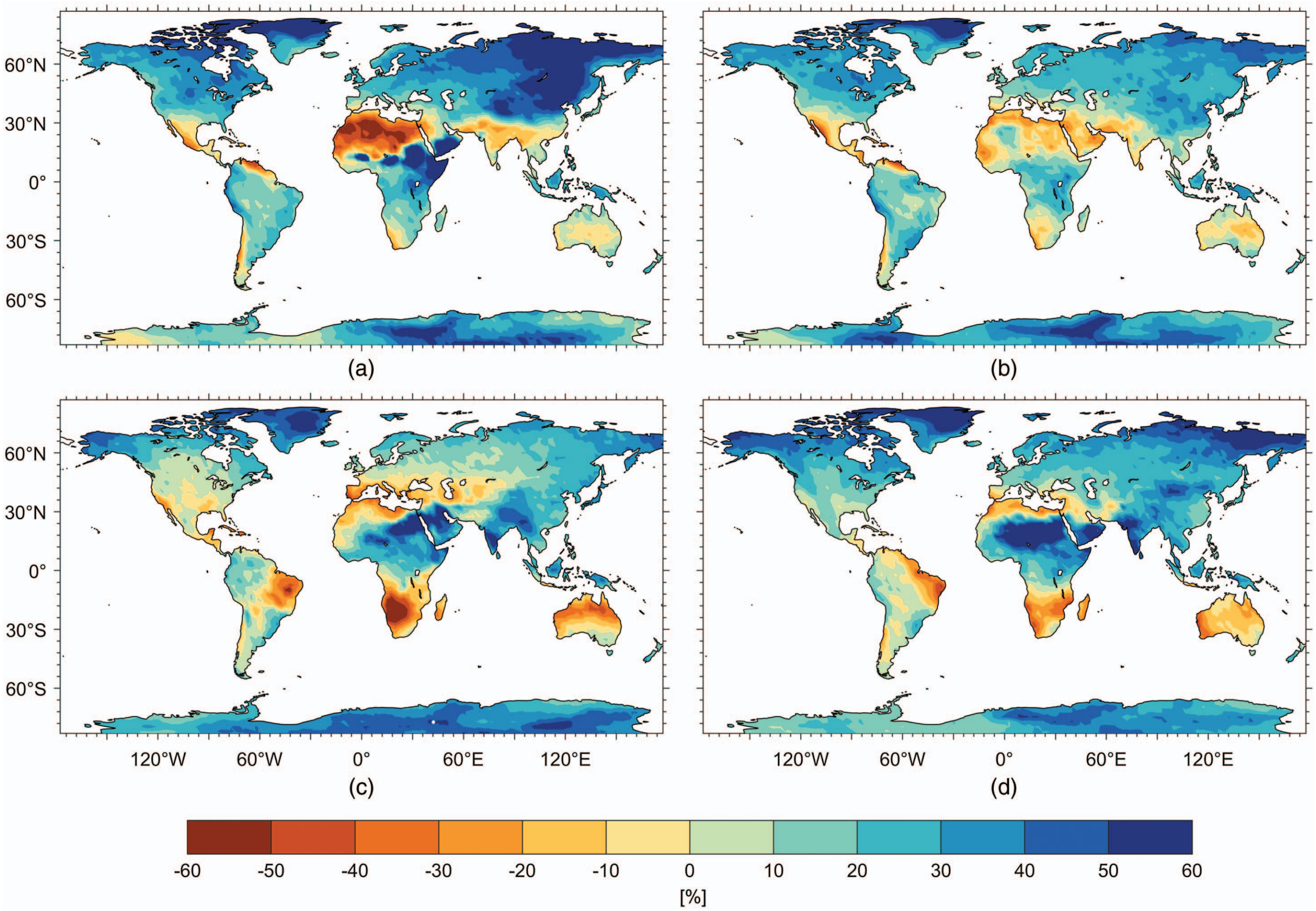

Fig. 4. (Color) Seasonal change (%) in maximum daily rainfall (Rx1day) for (a) DJF; (b) MAM; (c) JJA; and (d) SON between the future (2081–2100) and reference (1981–2000) periods for the RCP8.5 scenario.

ensemble simulation was selected for the reference (1981–2000) and future (2081–2100) periods. The seasonal (December-January-February, DJF; March-April-May, MAM; June-July-August, JJA; and September-October-November, SON) Rx1day and mean temperature were calculated for both the reference and future periods and then remapped on a common $2.5° \times 2.5°$ grid to compute the multimodel ensemble mean. The $R_{sc,24,2}$ scaling rates were obtained through the ratio of the projected changes of Rx1day (Fig. 4) and mean temperature (Fig. 5). The $R_{sc,24,2}$ scaling rate for the RCP8.5 scenario is shown in Fig. 6 (the scaling rate of the RCP4.5 scenario is shown in Fig. S1). Similar to those by Seneviratne et al. (2016), the scaling ratios are found to be roughly similar for both the RCP4.5 and RCP8.5 emission scenarios.

The projected change in mean seasonal temperature (ΔT), needed to compute Eq. (2), is shown for the RCP8.5 scenario over the 2081–2100 period in Fig. 5. Results for other future time horizons (2021–2040, 2041–2060, and 2061–2080) are available in Figs. S2–S4. By specifying a projected change in mean seasonal temperature (ΔT), the practitioner can determine the horizon of interest-based on the infrastructure's expected lifespan (e.g., up to the middle or the end of the 21st century). As discussed previously, the RCP8.5 business-as-usual scenario was preferred over the more optimistic RCP scenarios (e.g., RCP4.5) because it matches the current emissions (Sanford et al. 2014; Schwalm et al. 2020) and provides more conservative design criteria.

The seasonal and spatial heterogeneity of the changes in maximum daily rainfall presented (Fig. 4) and in the scaling rates (Fig. 6) are the consequence of multiple factors, which include large-scale atmospheric circulation changes that drive moisture convergence and local changes of near-surface air temperature and atmospheric conditions that affect convection (O'Gorman and Schneider 2009; Donat et al. 2016). Generally, extreme precipitation increases with temperature in moist, energy-limited environments and decreases in dry, moisture-limited environments (Prein et al. 2017b). Moreover, during the wet season, when there is a moisture surplus, extreme precipitation increases close to or above the Clausius-Clapeyron rate, while the increase is smaller during the dry season (Tabari 2020).

Fig. 6 presents the scaling of the median Rx1day corresponding to the 24-h 2-year return period rainfall. A strong worldwide seasonal variation is found in the scaling rates, depending on the time of occurrence of the annual daily maximum rainfall. We recommend selecting a scaling rate based on the season that displays the largest annual daily maximum rainfall (Fig. 7). Most regions project positive scaling factors, with some level of regional variability. For instance, the scaling rates of most regions in Eastern North America vary between 4%/°C and 6%/°C for the winter (DJF) and autumn (SON). Warm regions with less available moisture (e.g., Southern Spain, the Maghreb, South Africa, and Australia) exhibit negative rates.

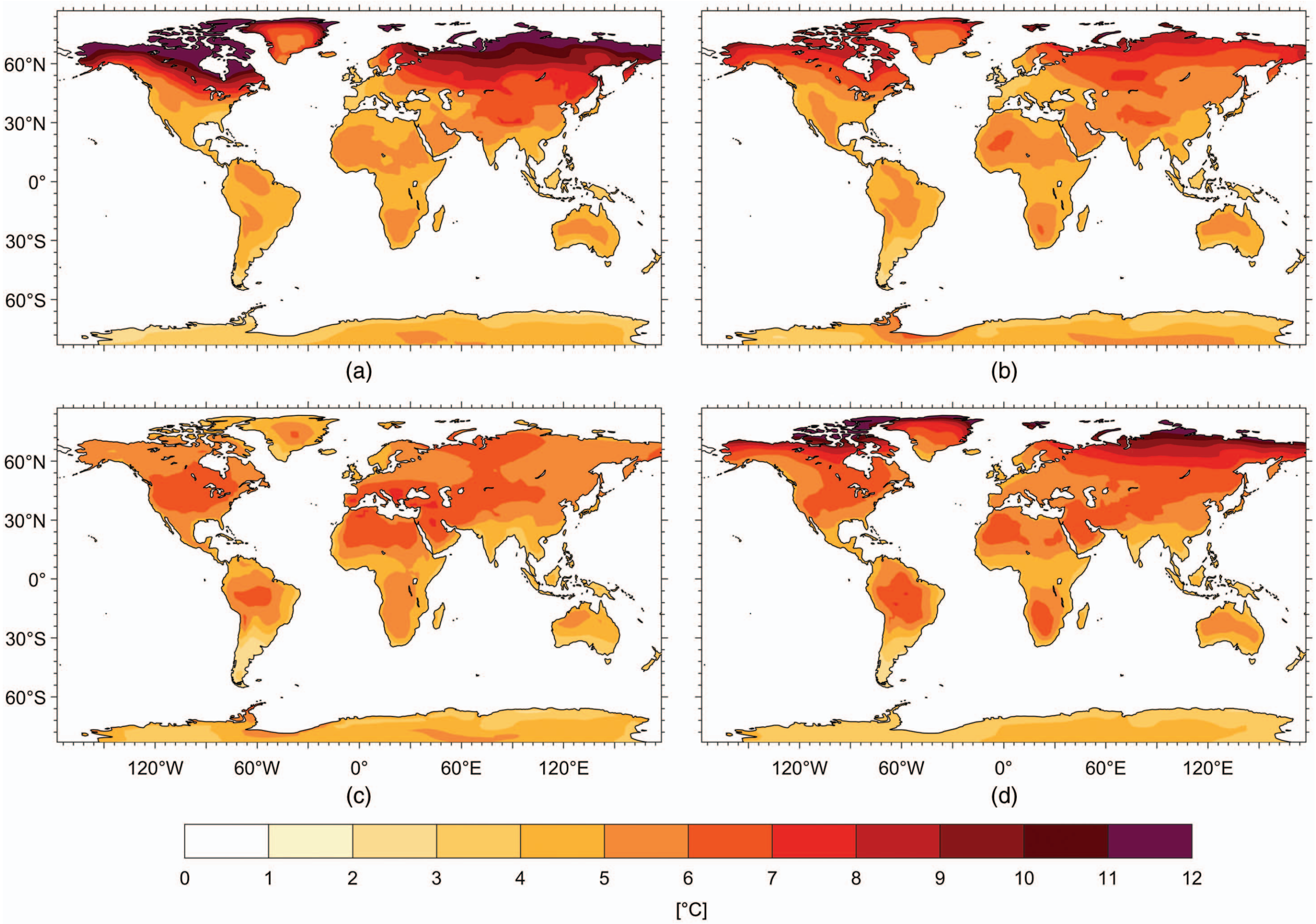

Fig. 5. (Color) Seasonal temperature change (°C) for (a) DJF; (b) MAM; (c) JJA; and (d) SON between the future (2081–2100) and reference (1981–2000) periods for the RCP8.5 scenario.

For Eq. (2), we recommend using the ΔT and $R_{sc,24,2}$ scaling provided in Figs. 5 and 6, respectively, or to recompute local scaling factors using RCM and CPM ensembles according to the data availability and the practitioner's level of climate expertise.

Based on the literature review reported previously, it is currently not feasible to compute precise and reliable estimates of the duration (F_D) and frequency (F_T) factors. This is especially true for subhourly durations, for which high-resolution CPMs are required. The use of CPM ensembles, such as the one presented by Pichelli et al. (2021) over a domain centered over the Alps, will eventually allow estimating these two factors more accurately at the local scale. Considering the rate at which more and longer CPM simulations are being generated, reliable estimations of both factors are expected to be possible in the next decade. While a single CPM simulation could still be used to provide an initial estimation for these factors, it should be done with precaution, considering the different sources of uncertainties previously discussed. However, even an uncertain estimation would prove to be a better alternative than the status quo when it comes to building resilient infrastructure.

We can nonetheless provide the range of plausible values for each factor. Both factors are positive and equal to or greater than 1. The value of each factor will progressively increase above 1 as the rainfall duration decreases (from the 24-h reference duration) or as the rainfall return period increases (from the 2-year reference return period). The upper limit of both factors is given by their physical interpretation: coefficient values larger than 1.5 are unlikely as they would lead to an improbable super CC as compared to observations and climate model projections. Just as is the case for the scaling rate, these values will be region-dependent. A value of 1 indicates no amplification of rainfall extremes for durations shorter than 24 h (F_D) and return periods longer than 2 years (F_T).

Improvements will continue to be made in climate modeling, and it is expected that better spatial and temporal resolutions of climate models will lead to lower uncertainty in their simulations as the 21st century progresses. For these reasons, we strongly recommend that all the Eq. (2) components be periodically revisited (e.g., every 5 years) by using state-of-the-art climate models and ensemble simulations. Similar to the updating of IDF curves based on historical observations, the nonstationarity of the future climate must be considered, which will ultimately lead to a reduction of the overall uncertainty in infrastructure design.

Finally, the practitioner should keep in mind that no-regret strategies are likely a good option when dealing with climate uncertainty, as their excess adaptation cost can be relatively small when compared to potential consequences. Using the same analogy as before, choosing a culvert that can convey a 20-year flow or a 100-year flow is only a matter of choosing a slightly larger diameter. This is a much smaller cost than having to rebuild a section of road that has been washed away due to an underdesigned culvert.

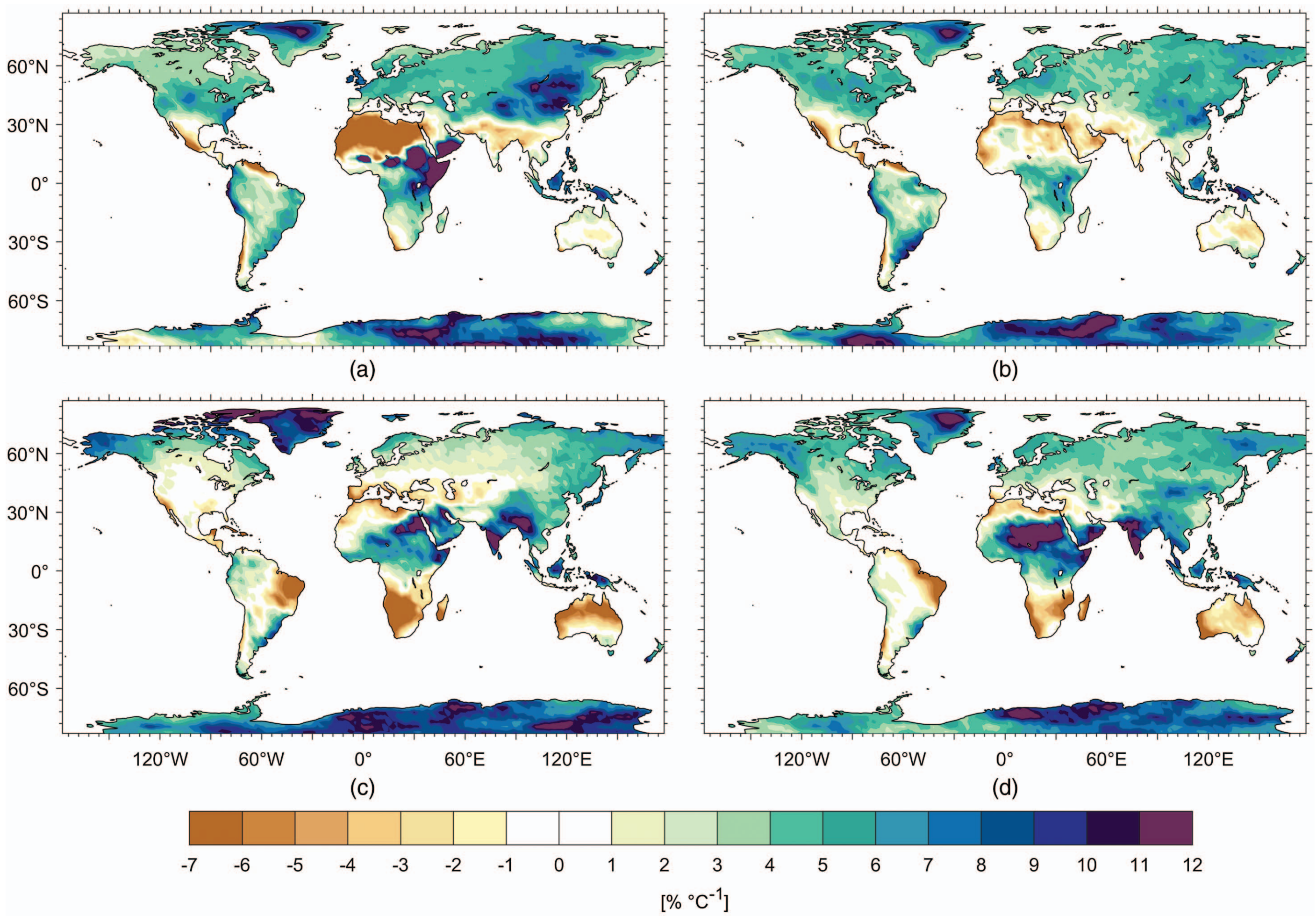

Fig. 6. (Color) Seasonal scaling rates (%/°C) of daily maximum seasonal rainfall (Rx1day) for (a) DJF; (b) MAM; (c) JJA; and (d) SON; with respect to global mean seasonal temperature changes for the RCP8.5 scenario.

Detection of the Climate Change Signal

Various trend detection methods were explored to determine if an anthropogenic climate change signal can be detected by using the observation networks of rain gauges. Globally, approximately two-thirds of daily rainfall stations display increasing trends for the latter half of the 20th century (Min et al. 2011; Westra et al. 2013). There is also considerable evidence of greater increases in subdaily rainfall extremes (Fowler et al. 2021a; Westra et al. 2014).

However, natural variability can represent a considerable source of uncertainty and could mask the climate change signal at both the local and regional scales (Deser et al. 2012; Fischer et al. 2013; Martel et al. 2018). Martel et al. (2018) show that the detection of a significant trend at the regional scale could be delayed until the middle of the 21st century in many parts of the world. In the case of local trends, the role of natural variability is even greater, and the detection of a significant trend could be further delayed until the end of the century.

The studies used in this paper lead to an overwhelming consensus: extreme daily and subdaily rainfall events are expected to increase significantly in response to a warmer climate (Fig. 3 and Table S1). Thus, for regions where no trend is observed in rainfall data, a seemingly absent trend should not prevent the implementation of adaptation measures against climate change, especially for infrastructures with a long service life.

Conclusion

Due to the observable shift in the recent climate and the expected changes in the future, engineers cannot continue to rely on codes, standards, and professional guidelines that are solely based on historical climate information when designing structures with a long lifespan. In such cases, failing to consider the impact of climate change could be considered as a breach of an engineer's standard of care (ASCE 2018; Engineers Canada 2018). Addressing the challenges of an evolving climate is necessary to ensure that any new infrastructure provides a service level adapted to both current and future climates.

This paper provides a literature review on extreme rainfall events, looking at trends in both the recent observational records as well as in future projections from climate models, including global climate models (GCMs), regional climate models (RCMs), and convection-permitting models (CPMs). From this review, a strong consensus emerges on the increase of extreme rainfall events in a warmer climate over most land regions of the world. GCMs and RCMs provide consistent patterns of increasing extreme rainfall events at the daily and subdaily (for RCMs) scales, and CPMs have recently opened a window on subhourly rainfall extreme events, a time scale especially relevant to many engineering applications. The intensification of extreme rainfall in a warmer climate is a settled scientific issue, and the challenges are now to determine the rates of change and factors governing these rates.

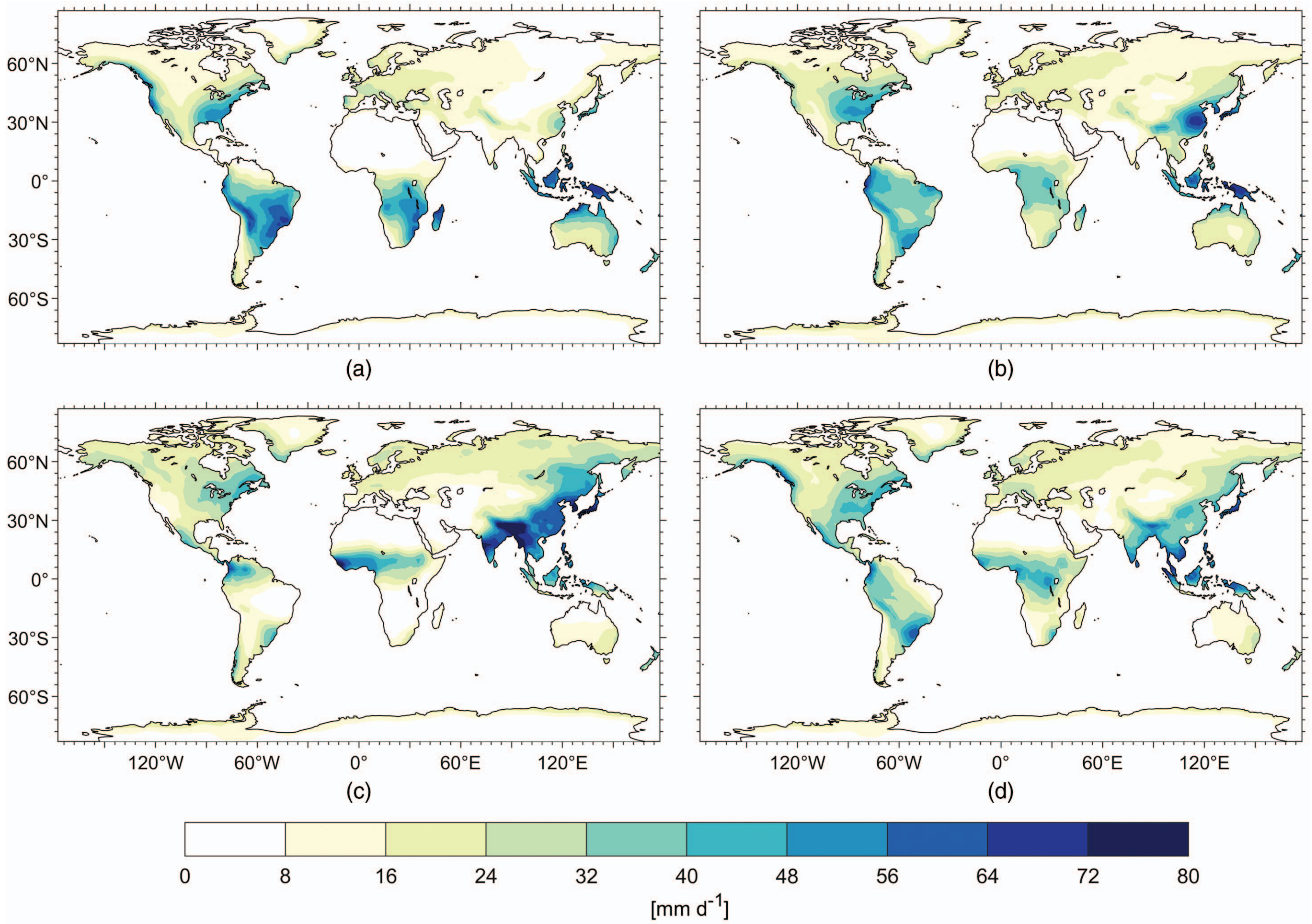

Fig. 7. (Color) Seasonal daily maximum rainfall (Rx1day in mm) for (a) DJF; (b) MAM; (c) JJA; and (d) SON over the future (2081–2100) period for the RCP8.5 scenario.

The patterns of increasing extreme rainfall events are complex and regionally dependent. State-of-the-art climate models cannot currently provide reliable estimates of the scaling factors of subhourly and longer return period extremes of precipitation with temperature, but they are rapidly improving. However, some important conclusions can be drawn with the current state of knowledge, and actions can be taken today to mitigate the upcoming impacts of climate change better. Over most of the land areas, the scaling of the annual maximum rainfall (Rx1day) appears to be slightly below but close to the Clausius-Clapeyron scaling. However, the scaling of extreme rainfall is frequency- and duration-dependent, with lower frequency (longer return period) and shorter-duration rainfall experiencing larger scaling, including up to super Clausius-Clapeyron scaling in many parts of the world. This frequency-duration dependency is particularly critical to engineers who routinely use design rainfall with very long return periods ($T >$ 20 years) and subhourly durations, which will be the most affected by potential super Clausius-Clapeyron scaling.

Adaptation strategies have already been put in place by some regulatory/legislative bodies with respect to IDF curves used by engineers. These strategies are a step in the right direction, but they do not recognize the impact of frequency, and especially duration, on the amplification of future extreme rainfall, with potentially very large increases for subhourly and very low-frequency rainfall events. It is hoped that this work will be useful in helping shape better guidelines for the adaptation of IDF curves for a future warmer climate. Future work should focus on improving the representation of extreme rainfall events in climate models, reducing the uncertainty, and increasing the robustness of the local scaling factors to integrate the frequency and duration of extreme events in rainfall design.

Data Availability Statement

All data, models, and code generated or used during the study appear in the published article.

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model output. For CMIP, the USDOE's Program for Climate Model Diagnosis and Intercomparison provided coordinating support and led the development of software infrastructure in partnership with the Global Organization for Earth System Science Portals. The authors also extend their gratitude to the anonymous reviewers whose comments helped shape the paper in its current form.

Supplemental Materials

Tables S1 and S2 and Figs. S1–S4 are available online in the ASCE Library (www.ascelibrary.org).

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