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ADVANCED REVIEW

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Extreme precipitation events

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Abstract

The effect of increased populations concentrated in urban areas, coupled with the ongoing threat of climate change, means that society is becoming increasingly vulnerable to the effects of extreme precipitation. The study of these events is therefore a key topic in climate research, in their physical basis, in the study of their impacts, and in our adaptation to them. From a meteorological perspective, the main questions are related to the definition of extreme events, changes in their distribution and intensity both globally and regionally, the dependence on large-scale phenomena including the role of moisture transport, and changes in their behavior due to anthropogenic pressures. In this review article, we address all these points and propose a set of challenges for future research.

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extreme precipitation, extreme threshold definition, global moisture transport, observed and future changes

1 | INTRODUCTION

Over the last few decades, the study of extreme events has become a focus of interest for society due to their social, economic, and environmental impacts (Ackerman, 2017; Alimonti et al., 2022; Lugo, 2018; Wernberg et al., 2013). Whether related to higher population densities in specific areas (United Nations Department of Economic and Social Affairs, 2019), or an increased dependence on critical infrastructure (for telecommunications, healthcare, or other services; Turoff et al., 2016) some societies are now particularly vulnerable to the impact of extreme events. Extreme events caused by natural hazards or/and human actions may in turn trigger natural and technological disasters (Girgin et al., 2019; Haddow et al., 2020). The cascading impacts of multi-hazard types have been described for historical catastrophic events such as the impact of Hurricane Irma on the Caribbean and the southeast of United States (Emrich et al., 2019) or the 2004 Indian Ocean Tsunami and 2011 great East Japan earthquake and tsunami (Suppasri et al., 2021).

Extreme events are investigated in a number of different fields such as social sciences, ecology, and engineering; however, weather and climate extremes—specifically precipitation—have attracted the most interest in the recent literature (McPhillips et al., 2018). Variations in the distribution and intensity of precipitation patterns have attracted a great deal of scientific interest due to the particular threat to human activities posed by extreme hydrological events such as extreme precipitation, and floods. Among the most recent catastrophic events, there are some worth mentioning; eastern China in June 2015 (Wang & Gu, 2016), western Europe in July 2019 (Science, 2021), or southeast Brazil in 2020 (Dalagnol et al., 2022); all of them causing catastrophic socio-economic and environmental impacts. Climate extremes demand preparedness and emergency response strategies that go beyond the emergency response services, including health and social care providers (Curtis et al., 2017). A recent study also confirmed that extreme rainfall reduces worldwide macroeconomic growth rates and slows the global economy rise (Liang, 2022).

There is growing evidence that anthropogenic activity affects the climate in numerous ways, and the effects of extreme conditions are likely to become stronger due to changes in their intensity and frequency. In particular, the intensity of extreme rainfall is expected to increase in regions with high moisture availability, particularly in wet moths. This will cause more frequent and severe flooding under global warming (e.g., Min et al., 2011; Pall et al., 2011; Tabari, 2020). Despite the current observational uncertainties of extreme rainfall (Herold et al., 2017), increasingly extreme rainfall has been reported in a large number of locations, even in regions where the average rainfall has decreased (e.g., Asadieh & Krakauer, 2015; Kharin et al., 2007; Kharin & Zwiers, 2005). The precipitation budget will be therefore affected, becoming a challenge to water resources management (Zittis et al., 2021). It is therefore of great interest to understand the changing characteristics and impacts of extreme precipitation events as part of attempts to design adaptation and mitigation policies that could allow improvements to be made in terms of the ability of society to adapt to potential changes caused by global warming (IPCC, 2013, 2021). However, modeling precipitation and detecting extreme events in future scenarios is challenging today; models still simulate varying magnitudes of precipitation response to anthropogenic forcing. This is mostly due to the use of different schemes for parameterizing processes at the subgrid-scale (Madakumbura et al., 2021). Uncertainties also arise regarding the future behavior of major mechanisms of atmospheric moisture transport and their role in the occurrence of extreme precipitation events under global warming (Gimeno et al., 2016).

In this review, we intend to address the phenomenon of extreme precipitation from several aspects, including its definition, the physical fundaments, generating mechanisms, spatiotemporal evolution, and future challenges. First, when approaching the study of extreme precipitation events it is important to clarify the definition of "extreme", a term that can have different meanings related to causes as fundamental as moisture transport mechanisms to effects such as natural hazards. The definition must also acknowledge different statistical techniques, from the very simple (such as the use of fixed precipitation thresholds) to more sophisticated (such as those derived from the application of the Extreme Value Theory). Sections 2 and 3 are therefore devoted to these aspects of the definition. Leaving aside some of the more detailed theoretical considerations; in Section 4, we will address the essential physical basis that underpins how the extremes of precipitation have changed over the last few decades and should change in the decades that follow, as a consequence of increased global temperatures. These observed and predicted changes will form the content of Section 5. In Section 6, we will address the intriguing role of moisture transport and its major mechanisms related to the extremes of precipitation, and finally, in the last section, we will formulate some of the main challenges for future research.

2 | THE PROBLEM OF DEFINING EXTREMES

As addressed in the introduction, the definition of "extreme" is not unique. Despite the increased use of the term, a unified definition of the word has never been achieved, either in an interdisciplinary sense or in specific research fields (McPhillips et al., 2018; Brosca et al., 2020). This section will address this issue from two different approaches. On the one hand, the perspective related to the disaster aspects. On the other hand, the perspective is based on the statistical approach to the amount of precipitation. In the latter, parametric and nonparametric—including indices used by Expert Team on Climate Change Detection and Indices (ETCCDI)—statistic methods will be introduced. Moreover, some alternatives to these methods will be discussed.

In general terms, and related to the disaster aspects, extreme events can be considered in terms of either their nature or their impacts. Despite the general use of impacts (economic losses, social effect) to define extreme events in some disciplines, in the climatological sciences extreme events are usually defined in terms of the anomaly of their occurrence and specifically by their characteristics (McPhillips et al., 2018). Despite the common association of "unusually rare" events (in terms of magnitude) with more severe impacts, in the last few decades, many important economic losses and environmental impacts have also been associated with nonextreme events. A number of factors can be attributed to these losses, and in many cases, unusually extreme impacts have been attributed to a combination of different types of events in different regions. For example, precipitation in combination with storm surges is expected to produce important coastal flooding in the future (Bevacqua et al., 2019; Ridder et al., 2018). The increased occurrence of this kind of damage has increased levels of interest in so-called "compound events", defined as the combination of variables or events that lead to an extreme impact (Leonard et al., 2014), even though the individual events may not necessarily be extreme in themselves.

Among the many different statistical techniques available for the definition of extreme precipitation, the easiest and probably the most widely used in literature are nonparametric methods based on the use of fixed values or percentiles to select a threshold for extreme events (Anagnostopoulou & Tolika, 2012). Following this methodology, the Expert Team on Climate Change Detection and Indices (ETCCDI) developed a set of 27 indices based on daily temperature and precipitation, which are used extensively to detect and monitor climate change (e.g., Alexander & Arblaster, 2017; Cooley & Chang, 2020; Yin & Sun, 2018). From this list, 10 indices are linked specifically to precipitation as presented in Table 1. Some of the precipitation indices are defined in terms of a specific value (such as 10 mm, 20 mm, or a user-defined threshold), with the index based on the number of days on which the threshold is exceeded over a given period. This type of index can be useful for specific purposes or for particular areas, although a percentile-based method is in general more suitable for allowing comparisons to be made between regions. For this reason, most authors use a percentile-based index, with the percentile ranging between 90 and 99 (McPhillips et al., 2018). While most ETCCDI indices are based on the analysis of precipitation on single days, the definition of extreme events can also be expressed in terms of the duration of a particular characteristic of precipitation, by defining extreme precipitation events as a number of consecutive days with precipitation above a threshold (She et al., 2015). For the definition of threshold-based extreme events, an important consideration is the sensitivity of the results to the selection of the threshold, which can lead to misinterpretation of results in some cases (Pendergrass, 2018; Schär et al., 2016). While it is clearly not possible to define a single fixed threshold for extreme precipitation for different regions, it is also clear that percentile-based thresholds are not always able to characterize extreme events fully. In both cases, the results depend strongly on the selection of the threshold; in most cases, this is determined arbitrarily. For example, almost 90% of the precipitation falls above the 95th precipitation percentile in some regions if all days are taken into consideration in the computation (Pendergrass, 2018). However, usually only precipitation days (with precipitation higher than 1 mm) are considered in

TABLE 1 Precipitation indices defined by the ETCCDI

Index	Definition
R10mm	Annual count of days when precipitation (PRCP) ≥ 10 mm
R20mm	Annual count of days when PRCP ≥ 20 mm
Rnnmm	Annual count of days when PRCP ≥ nn mm, nn is a user-defined threshold
RX1day	Maximum 1-day precipitation
RX5day	Maximum of consecutive 5-day precipitation mm
SDII	Ratio of annual total precipitation to the number of wet days (≥1 mm).
R95p	Amount of precipitation from days >95th percentile
R99p	Amount of precipitation from days >99th percentile
CWD	Maximum number of consecutive days with RR ≥1 mm
PRCPTOT	Annual total precipitation on wet days

the percentile computation according to Schär et al. (2016), but this methodology can also lead to artifacts and misleading results if significant variations in wet-day frequency are not taken into account.

The limitations of nonparametric techniques have led to increased interest in the use of different methods to investigate extreme events, including the parametric methodologies that have seen widespread use over the last few decades. The most common parametric method is the extreme value distribution fitting method, which is based on the use of probabilistic statistical techniques and precipitation data, in order to establish a threshold for the occurrence of extreme events (Liu et al., 2013). Several distribution functions can be applied in these methodologies, including the generalized Pareto distribution and the generalized extreme value distribution (Lazoglou et al., 2019), which will be discussed in Section 3.

Different authors have pointed to the better accuracy of parametric compared with nonparametric methods to define extreme precipitation (e.g., Anagnostopoulou & Tolika, 2012), although these methodologies also have limitations, such as the sensitivity to the size of the data series in the nonparametric percentile method or the discrepancies in the return periods between different parametric techniques (Lazoglou et al., 2019; Liu et al., 2013). For this reason, other methods have also received consideration, including detrended fluctuation analysis, which is the most popular alternative to both parametric and nonparametric methods. Detrended fluctuation analysis is an attempt to define objectively the threshold for extreme events by filtering the short-range dependence and any other trends of non-stationary time-series, thereby allowing detection of any long-range dependence in the data (Liu et al., 2013). The robustness of this methodology has been shown for different regions such as the Pearl River Basin (Liu et al., 2013) and the Loess Plateau of China (Zhang et al., 2020). However, the complexity of the calculation and the need for long series of rainfall (Liu et al., 2013) make this method less popular than others.

Despite an increased attention to extreme precipitation, there is no consensus on which methodology is the best for defining extreme events. The existence of many different methodologies with their advantages and disadvantages means that the proper understanding of the basis behind each of them is critical. A better understanding of each methodology could allow us to select the most suitable one for each case in order to allow the proper interpretation of results.

3 | EXTREME VALUE STATISTICS: FUNDAMENTALS AND APPLICATIONS

In climate science, extreme phenomena are of great interest; however, in most cases, there are few observations or none at all. In order to estimate the tail of the distribution of the relevant environmental random variable (e.g., precipitation, wind speed, etc.), a number of statistical techniques are available, which are derived from the so-called Extreme Value Theory (EVT). In this section, we will introduce some of the basic concepts that are widely used across many fields of knowledge.

We consider $X_1, X_2, ..., X_n$ as independent random variables, identically distributed to X, with distribution function F. Although our focus is on maxima, it is not restrictive because equivalent results for minima can easily be found by taking into account the fact that $\min(X_1, ..., X_n) = -\max(-X_1, ..., -X_n)$.

It is well known that the suitably normalized maximum converges to a distribution G that is not degenerate and is of the same type as one of these distributions ("the same type" means that the only differences are in location or scale):

- Type 1: (Gumbel): $\mathrm{G}(x) = \Lambda(\mathrm{x}) = \exp(-\exp(-x)), \text{for } \mathrm{x} \in \mathbb{R}$.
- Type 2: (Fréchet): $G(x) = \Phi_\alpha(x) = \begin{cases} 0, x \le 0 \\ \exp(-x^{-\alpha}), x > 0, \alpha > 0 \end{cases}$
- Type 3: (Weibull): $G(x) = \Psi_\alpha(x) = \begin{cases} \exp(-(-x)^\alpha), x < 0, \alpha > 0 \\ 1, x \ge 0 \end{cases}$

Von Mises (1954) and Jenkinson (1955) unified the three families into the Generalized Extreme Value (GEV) distribution, with distribution function:

$$G_\gamma(x; \mu, \sigma) = \begin{cases} \exp\left(-\left(1 + \gamma\frac{\mathrm{x}-\mu}{\sigma}\right)^{-\frac{1}{\gamma}}\right), & (\gamma \neq 0), \\ \exp\left(-\exp\left(-\frac{\mathrm{x}-\mu}{\sigma}\right)\right), & (\gamma = 0), \end{cases}$$

where $1+\frac{\gamma(x-\mu)}{\sigma}>0, \mu\in\mathbb{R}$, $\sigma>0$ and $\gamma\in\mathbb{R}$; μ is the location parameter, σ is the scale parameter, and γ is the shape parameter. If $\gamma<0$, the tail of the distribution of X is lighter than that corresponding to the exponential distribution (and F is of the Weibull type); if $\gamma=0$, the tail is exponential (and F is of the Gumbel type); and if $\gamma>0$, the tail is heavier than exponential (and F is of the Fréchet type).

By denoting $Y:=\max(X_1,...,X_n)$, it is possible to approximate its distribution using a $GEV(\gamma;\mu,\sigma)$. We can partition the observations X_i into blocks; for example, if our data consist of 30 years of daily observations of precipitation, we will have 30 blocks of 365 observations each. Therefore, we will be considering $Y_1, Y_2, ..., Y_{30}$ as a sample Y of dimension 30. This statistical approach is usually termed "block maxima."

At this point, there are some important concepts to mention:

- *Exceedance probability*: This is simply the probability that Y is greater than a predefined large value q, that is, $P(Y>q)\approx 1-G_\gamma(q;\mu,\sigma)$.
- *Return level*: For a given T, the return level is $U(T)$ such that $P(Y>U(T))=\frac{1}{T}$. For example, by taking Y as the annual maximum of precipitation, the 100-year return level, or $U(100)$, is such that, on average, Y is greater than that quantity once every 100 years. $U(T)$ can be expressed in terms of the GEV distribution: $U(T)\approx \overleftarrow{G_\gamma}\left(1-\frac{1}{T};\mu,\sigma\right)$, where $\overleftarrow{G_\gamma}(y;\mu,\sigma)$ denotes the inverse of the GEV distribution function.
- *Return period*: For a given y_T, the return period is $T=\frac{1}{P(Y>y_T)}\approx 1/\left(1-G_\gamma(y_T;\mu,\sigma)\right)$. In our example, the annual maximum of precipitation is, on average, greater than y_T once every T years.

We can obtain estimates of these quantities by substituting the unknown parameters of the GEV distribution with their corresponding estimates (the most common estimation methods are maximum likelihood and probability weighted moments).

In another statistical approach known as Peaks-Over-Threshold (POT), observations greater than a large threshold u are analyzed and the differences are calculated between each of these observations and u. If we denote $W:=X-U$, we are studying the distribution of the random variable $W \mid W>0$, which can be approximated quite well by a Generalized Pareto (GP) distribution. Taking F_u as the distribution function of W and $H_\gamma(w;\sigma)$ as the distribution function of a GP distribution with shape parameter $\gamma\in\mathbb{R}$ and scale parameter >0 we have:

$$F_u(w)\approx H_\gamma(w;\sigma)=\begin{cases}1-\left(1+\frac{\gamma w}{\sigma}\right)^{-\frac{1}{\gamma}}, w\in(0,\infty), \gamma>0\\ 1-\exp\left(-\dfrac{w}{\sigma}\right), w\in(0,\infty), \gamma=0\\ 1-\left(1+\frac{\gamma w}{\sigma}\right)^{-\frac{1}{\gamma}}, w \quad \left(0,-\dfrac{\sigma}{\gamma}\right), \gamma<0\end{cases}$$

This approximation was first described by Pickands (1975) and Balkema and de Haan (1974). An interesting example of its use is as follows.

Taking the random variable X as the "amount of precipitation", we extract a sample of X of dimension n. For instance, our data may consist of n daily observations of precipitation. We can calculate the (approximate) probability that X is greater than the largest observation recorded over these n days, denoted $x_{(n)}$. Let N_u be the number of observations of the sample that exceed; with $w_{(N_u)}$ as the largest observation of the variable W we can write:

$$P\left(X>x_{(n)}\right)=\{1-F(u)\}\left[1-F_u\left(w_{(N_u)}\right)\right]\approx\frac{N_u}{n}\left(1-H_\gamma\left(w_{(N_u)};\sigma\right)\right),$$

we also note that $1-F(u)\approx\frac{N_u}{n}$.

In order to obtain an estimate of this probability, γ and σ must be substituted by their corresponding estimates (as for the "block maxima" approach, maximum likelihood and probability weighted moments are the most popular methods of estimation).

The problem of choosing the value of the threshold u is open and controversial. Davison and Smith (1990) proposed the study of the mean excess function, which in the case of the GP distribution, takes the form:

$$e(t) := E(X - t \mid X > t) = \frac{\sigma + \gamma t}{1 - \gamma}, \textit{if } \gamma < 1$$

In practice, it consists of choosing u such that the plot of $\widehat{e}_n(t)$ is approximately linear to the right of that value. $\widehat{e}_n(t)$ is the empirical version of $e(t)$ and can be expressed as:

$$\widehat{e}_n(t) := \frac{\sum_{i=1}^{n} x_i \mathbf{1}_{(t,+\infty)}(x_i)}{\sum_{i=1}^{n} \mathbf{1}_{(t,+\infty)}(x_i)} - t, \text{ where } \mathbf{1}_{(t,+\infty)}(x_i) = \begin{cases} 0, & x_i \le t \\ 1, x_i > t \end{cases}.$$

Further information about threshold selection can be found in Beguería (2005).

Finally, it is important to note that throughout this section we have been considering that the parameters of the distributions are constant over time. However, in the context of climate change, they may be time-dependent (this is called "nonstationarity"). One way of solving this problem is by reformulating the parameters of the distributions, for example, in the case of the *GEV* model, we can write:

$$\mu(T) = \alpha_0 + \alpha_1 T,$$

$$\sigma(T) = \exp(\beta_0 + \beta_1 T),$$

$$\gamma(T) = \delta_0 + \delta_1 T.$$

Likewise, it is also possible to write the parameters of the *GP* distribution as $\sigma(T)$ and $\gamma(T)$, according to the same functional relationships indicated in the case of the *GEV* model, for example. The approach that consists of fitting a *GP* distribution with parameters that are allowed to vary with time is called "nonstationary POT", which is also very useful to model extreme precipitation (see, for instance, Beguería et al., 2011).

Aside from some technical limitations (it is difficult to maximize the log-likelihood function), the linear equations above may not be sufficiently accurate to express the true time dependence of the parameters (this difficulty is especially acute for long series). In order to cope with nonstationarity without dealing with the limitations of the linear forms, an alternative approach is the use of an inhomogeneous Poisson process, which incorporates a time-dependent occurrence rate $\lambda(T)$.

Last but not least, it is important to mention that extreme value analyses of precipitation tend to have a spatial dimension, in the sense that it is usually interesting to study the precipitation over large regions. Taking into account that the parameters of the distributions do not change so much when moving from one location to another one that is close to it, the purpose of the regional extreme-value analysis is to find a model (with a common shape parameter) that is valid for a homogeneous region. Nevertheless, it is possible to use spatial interpolation techniques to produce continuous maps of the parameters, making it easier to estimate spatially the extreme quantiles (see, e.g., Beguería & Vicente-Serrano, 2006; Beguería et al., 2009).

4 | RESPONSE OF PRECIPITATION EXTREMES TO WARMING

One of the main signs of climate change is the relentless rise in global average temperature. From a thermodynamic perspective, a warmer atmosphere leads to an increase in moisture content and to changes in the hydrological cycle, which include an intensification of precipitation. The increase in global mean precipitation is estimated to scale from 1% to 3% per degree of global mean temperature, limited by the atmospheric energy balance (e.g., Held & Soden, 2006; O'Gorman & Schneider, 2009). This increase is well below the Clausius–Clapeyron rate, where the global mean water vapor increases at a rate of 7% for each degree of increase in surface temperature (e.g., Held & Soden, 2006; O'Gorman & Muller, 2010). Additionally, the estimate of an increase in mean precipitation is not always supported by observations (Gu & Adler, 2015). The reason may be that the cloud radiative feedback is not properly represented by climate models or that the expected increase in global average precipitation due to increased emissions has been masked by aerosol drying, as suggested by different authors (Mauritsen & Stevens, 2015; Salzmann, 2016).

In any case, it is not expected that the increase in precipitation extremes will keep pace with the overall increase in mean precipitation. Some authors noted in the past that the intensity of the extremes of precipitation should increase in proportion to the average content of the atmospheric water vapor or at least at a similar rate as the climate warms (e.g., Allen & Ingram, 2002; Trenberth et al., 2003). Nevertheless, the intensity of the extreme precipitation is not limited by the global energy balance because this relates to the mean precipitation on a global scale, thus the rate of increase may be greater with global warming (Myhre et al., 2019; O'Gorman et al., 2012). The relationship between temperature and extreme rainfall is more complex than that suggested by the Clausius–Clapeyron equation. In fact, several regional studies have shown how the intensity of extreme rainfall increases more markedly at higher temperatures, especially for extreme rainfall events of short duration (Hardwick-Jones et al., 2010; Lenderink et al., 2011; Lenderink & Van Meijgaard, 2008).

O'Gorman and Schneider (2009) indicate a latitudinal effect where the extremes of extratropical precipitation may scale more slowly than the atmospheric water vapor content; extremes of tropical precipitation may not be simulated reliably due to highly variable changes in convection. In fact, extreme tropical precipitation events are mostly linked to long-term convective systems (Roca & Fiolleau, 2020), therefore the rate of increase of extreme precipitation could be higher if there is an increase in convective upward vertical flows. O'Gorman et al. (2012) showed an increase in extreme tropical precipitation events close to 10% for each degree of surface temperature, higher than that estimated for extratropical latitudes. Kharin et al. (2013) showed how the current simulated precipitation extremes according to return values determined as the quantiles of a Generalized Extreme Value (GEV) are suitable for the extratropics, but the uncertainty is greater for tropical precipitation extremes in both models and observations. The GEV approach was already described in Section 3, and it is characterized by providing a probabilistic framework for analyzing extremes in the tails of the distributions. This feature contrasts with the one provided by the ETCCSI, based on total values or predefined thresholds.

The intensity and frequency of extreme precipitation events have increased in most regions (Alexander et al., 2006). Sun et al. (2007) showed a consistent shift toward more intense and extreme rainfall on a global scale and in several different regions. Their results indicate an increase in the frequency of extreme rainfall, which is much greater than the increase in its intensity. Therefore, in a warmer climate, extreme precipitation events are expected to be more frequent than in the current conditions, reaching an unprecedented magnitude throughout the 21st century (Giorgi et al., 2019). There is some consensus that under a warmer climate, extreme precipitation events will experience an amplification similar to that predicted by Clasius–Clapeyron for the saturation vapor pressure although slight variations will occur under different circumstances. It is important to bear in mind that dynamic and thermodynamic contributions may also play an important role. Emori and Brown (2005) examined the role played by thermodynamic and dynamic changes related to increases in extreme precipitation. Their results generally show that thermodynamic changes—increases in atmospheric moisture content linked with global warming—play a major role in the changes observed in extreme precipitation patterns in many parts of the world, while the effect of atmospheric dynamics (atmospheric circulation) has only a minor effect that is limited to lower latitudes. An equivalent study has been carried out more recently by Norris et al. (2019), showing that in mid-latitudes the thermodynamic trend dominates, resulting in a similar increase to the Clausius–Clapeyron rate. At (sub)tropical latitudes, however, the dynamic effect and hence the increase are higher. In overall terms, Tabari et al. (2020) have shown that a good classification of the increase in extreme precipitation events can be given as a function of water availability. Thus, he has shown that in humid areas the increase is similar to the Clausius–Clapeyron rate. For semi-humid regions the increase is significantly lower, not reaching 6% K^{-1}. In the water-limited regions, the increase drops to 5.62 and 5.45% K^{-1} for semi-arid and arid regions, respectively.

In recent decades, a great deal of progress has been made in understanding the response of extreme precipitation to global warming. However, it is necessary to consider the relationship between thermodynamic effects at the local scale, and the dynamic contribution. Without this deeper understanding, the dominant processes related to potential changes in extreme rainfall patterns will not be properly understood.

5 | TRENDS IN OBSERVED AND MODELED PRECIPITATION EXTREMES

Increases in both the frequency and intensity of extreme precipitation have been identified in observations (Ali & Mishra, 2018; Donat et al., 2019; Easterling et al., 2017; Ghosh et al., 2012; Hegerl et al., 2015; Lochbihler et al., 2017; Min et al., 2011; Solomon et al., 2007) and climate model simulations (Donat, Alexander, et al., 2016; Donat, Lowry, et al. (2016); Fischer & Knutti, 2016; Kendon et al., 2018; Kharin et al., 2013; Pendergrass & Hartmann, 2014; Scoccimarro et al., 2013; Toreti et al., 2013; Wang et al., 2017; Westra et al., 2014; Zobel et al., 2018). Assessment of the trends has been undertaken for different periods and regions using different datasets, which makes it difficult to establish clear comparisons and conclusions. Nevertheless, in this section, our aim is to summarize the latest findings in order to provide some worldwide essential conclusions.

On a global scale, observations of annual maximum daily precipitation have shown an increase of an average of 5.73 mm over 110 years (1901–2010), which corresponds to an increase of 10% K^{-1} in global warming since 1901 (Asadieh & Krakauer, 2015). For a shorter period (1979–2010), Chou et al. (2013) revealed that global mean precipitation tends to increase during the rainy season and decrease during the dry season. However, when the period of analysis was extended to include previous years (1950–2009), no change was found in the total rainy-season precipitation, while the total dry-season precipitation showed an increase (Murray-Tortarolo et al., 2017). Papalexiou and Montanari (2019) used high-quality daily precipitation records from all over the globe to identify and compare changes in the frequency and magnitude of daily extremes over the period 1964–2013. They found that large parts of Eurasia (Europe, western Russia, most of China), North Australia, and the mid-western United States of America showed positive trends in frequency, whereas regions with positive trends in magnitude were in Asia (Vietnam, Cambodia, and Thailand), Central Russia (North of Mongolia), and western Europe (from Portugal to northern Norway). For a longer period (1901–2010), Donat et al. (2013) found that most of the precipitation indices showed (partly significant) changes towards more intense precipitation over the eastern half of North America as well as over large parts of eastern Europe, Asia, and South America. Areas with trends showing less frequent and intense precipitation were observed around the Mediterranean, in Southeast Asia, and in the northwestern part of North America. These changes in extreme precipitation were found for the number of heavy precipitation days (R10mm) and for the contribution from very wet days (R95PTOT). Similar patterns of change were also found for the average intensity, frequency, and duration of extreme precipitation. In a separate study, Donat et al. (2016) analyzed long-term changes and interannual variability of precipitation extremes using the global land-based gridded fields of the ETCCDI indices (e.g., R10mm) for the entire 20th century, finding global tendencies of more intense rainfall during most of the period, with a major agreement between datasets after 1950. Analysis of annual daily maxima and precipitation on very wet days (defined as days with annual total precipitation >95th percentile) show positive changes in South America, Asia, and Africa (e.g., Donat et al., 2016). The assessment of Carvalho (2019), which used instrumental records and a review of previous findings, revealed evidence of upward trends in extreme precipitation (amount, intensity, and frequency) in many parts of the world, but these were particularly evident over the mid-latitudes of North America and the subtropics of South America.

In order to provide a global historical overview of extreme precipitation trends over the continents, indices of gridded land-based temperature and precipitation extremes were established in HadEX3 gridded land surface extreme indices (Dunn et al., 2020). This database offers 12 precipitation indices derived from daily, in situ observations at 17,000 stations across the world, with the results being recommended by the World Meteorological Organization (WMO) ETCCDI. This database extends from 1901 to 2018; however, here we discuss the indices R95PTOT, R99PTOT, CED, and PRCTOT for the period 1970–2018, considering the period 1961–1990 as a reference. Trend maps are shown in Figure 1. As illustrated, positive statistically significant trends ($p < 0.10$) of PRCTOT are observed in North America, Central America, Central Amazonia, and the La Plata region in South America, West Africa, northern Europe, parts of the Middle East, and Southeast Asia, northeast Russia, and the western half of Australia. Negative trends are less common, but are generally seen to cover part of Greenland, northeast Brazil, Peru, southern South America, the Southwest part of West Africa, the eastern half of the Iberian Peninsula, the northern part of the Indian Peninsula, part of Southeast Asia, and parts of Oceania and Papua New Guinea. The pattern of trends for consecutive wet days (CWD) is very similar to that described above, although in this case, negative trends seem to be more widespread. Trends in extreme values according to R95PTOT and R99PTOT show clear increases over major parts of North and South America, West Africa, Europe, and South East Asia. In contrast, regions with negative anomalies cover smaller regions in northeast Brazil, and some parts of Canada, Russia, Asia, and central Australia.

According to Pendergrass et al. (2017), the variability of precipitation in most climate models increases over a majority of global land areas in response to warming (66% of land shows a clear increase in the variability of seasonal mean precipitation). Furthermore, global and regional climate simulations driven by future scenarios of increasing CO_2 concentrations agree on the increase of precipitation intensity and extremes for continued warming in the future (Ali & Mishra, 2018; Hegerl et al., 2004; Kharin et al., 2007, 2013; Min et al., 2011; Wang et al., 2017; Wentz et al., 2007; Zobel et al., 2018), which could almost double for each degree of further global warming (Myhre et al., 2019). Regional climate models from the Coupled Model Intercomparison Project phase 5 (CMIP5) and the Coordinated Regional

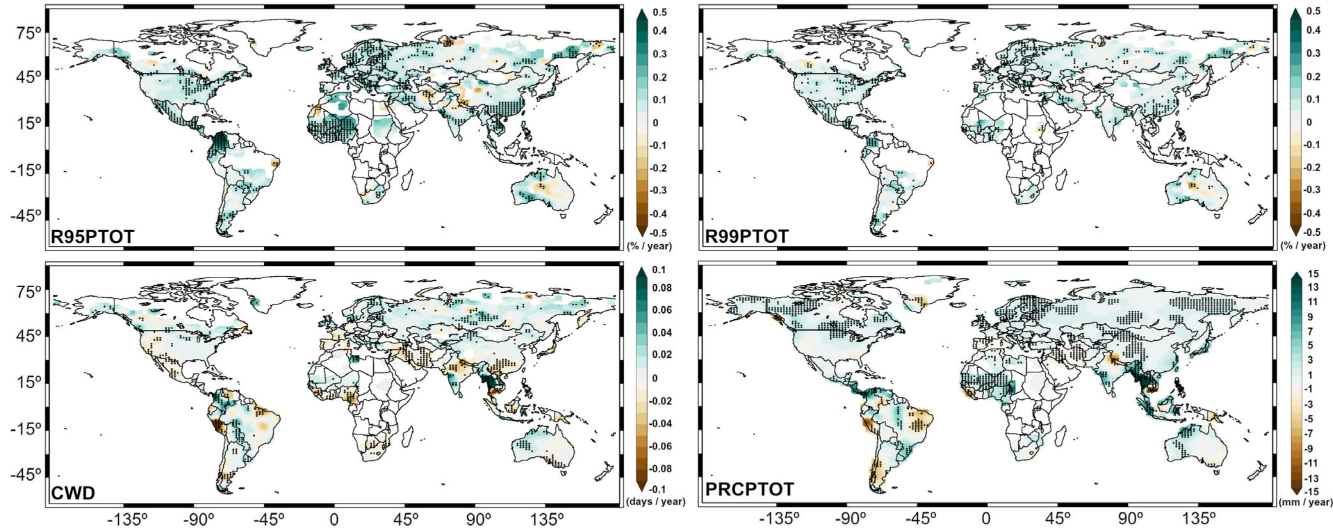

FIGURE 1 Linear trends in total daily precipitation exceeding the 95% (R95PTOT) and 99% (R99PTOT) percentile thresholds (top), and consecutive wet days (CWD) and total precipitation (PRCTOT) (bottom) for the period 1970–2018. Black dots represent statistically significant trends. Data from HadEX3: Peaks-Over-Threshold (Dunn et al., 2020)

Downscaling Experiment for 2071–2100 under the future emission scenario (Representative Concentration Pathways 8.5 W/m^2, RCP8.5) reveal that extreme precipitation could change substantially later in the year in most regions from summer toward autumn and winter (Marelle et al., 2018). However, this shift is not regionally homogeneous, and for the regions analyzed, it is strongest in northern Europe and northeastern North America (+12 and + 17 days, respectively), though local changes of more than a month are also likely. Despite the consensus, several differences exist regarding the spatial extent and intensity of increases or decreases in extreme daily precipitation, which depend also on the models and scenarios, but also on the statistical methods used. The uncertainty is significantly higher in dry regions than in wet regions (Kim et al., 2020).

According to Donat et al. (2016), despite uncertainties in the changes in total precipitation, extreme daily precipitation averaged over both dry and wet regimes shows robust increases in climate model projections for the rest of the 21st century. In addition, extreme precipitation according to r1X values under RCP8.5 are expected to increase over most continents by the last 30 years of the century, while decreasing in the subtropics, particularly the eastern ocean basins, extending to adjacent land areas, but representing just 1.5% of the total area (Pendergrass et al., 2017); the probability of flooding events would thus be increased in general terms (Fischer & Knutti, 2015; Fowler et al., 2021; IPCC, 2013; Kirchmeier-Young & Zhang, 2020; Mukherjee et al., 2018; Pall et al., 2011; Tabari et al., 2020). The general agreement regarding the increase in extreme precipitation this century is consistent with the Clausius–Clapeyron equation. An analysis based on precipitation for the CMIP5 outputs for the period 2006–2100 and considering the RCP8.5 scenarios as performed by Pfahl et al. (2017) revealed that thermodynamics alone would lead to a spatially homogeneous fractional increase, with different regional responses showing amplified increases in the Asian monsoon region, but weaker responses across the Mediterranean, South Africa, and Australia. In addition, over subtropical oceans, an appreciable regional decrease is predicted in extreme precipitation, which may partly result from a poleward shift in circulation (Hu et al., 2013; Nazarenko et al., 2015). Regional studies based on future simulations are thus crucial for identifying differences and making accurate comparisons to allow consideration of regional and local adaptation measures. Supporting Information includes a detailed description of the changes observed in Africa, the Americas, Europe, Asia, and Australia separately.

6 | ATMOSPHERIC MOISTURE TRANSPORT AND EXTREME PRECIPITATION

6.1 | Major moisture sources and extreme precipitation

The global transport of moisture is an important factor in the occurrence of extreme precipitation. Despite the generally local scales considered, the sources of moisture are diverse, and at the global scale, some regions are expected to contribute more to precipitation and hence to affect extreme precipitation events. Gimeno et al. (2010) defined the main global oceanic and terrestrial sources of continental precipitation as regions with higher values of divergence of vertical integrated moisture flux. By taking this into account, a total of 14 sources can be considered, shown in Figure 2 in annual terms. Most of the sources (11) are oceanic, and include some parts of the main Oceans (Atlantic, Pacific, or Indian Ocean) but also some enclosed Seas (Mediterranean or Red Sea). In addition to the oceanic regions, some continental sources are considered, such as Amazonia, the Sahel, or parts of southern Africa. Continental sources are especially relevant during the hemispheric winter. Update and revision of the effect of this moisture source on climatological and extreme precipitation over the continental areas in the peak precipitation month were undertaken by Nieto et al. (2019) and Vázquez et al. (2020), respectively. According to these authors, the contribution of these sources to continental precipitation shows contrasting behavior for mean precipitation compared with extreme events. Despite good agreement in terms of the primary source affecting most of the climatological and extreme precipitation over the continental areas, some differences in the extent of the influence may be observed. For extreme precipitation events (those with precipitation above the 95th percentile from monthly precipitation), transport from western oceanic areas seems to be favored. For example, the North and South Pacific increase their influence over eastern North and South America, respectively. The same phenomenon can also be seen in the Mediterranean and North Atlantic sources in Europe. Despite the increased area of contribution for some of the main global moisture sources, the results presented by Vázquez et al. (2020) suggest than for extreme precipitation events, the influence of local or other sources

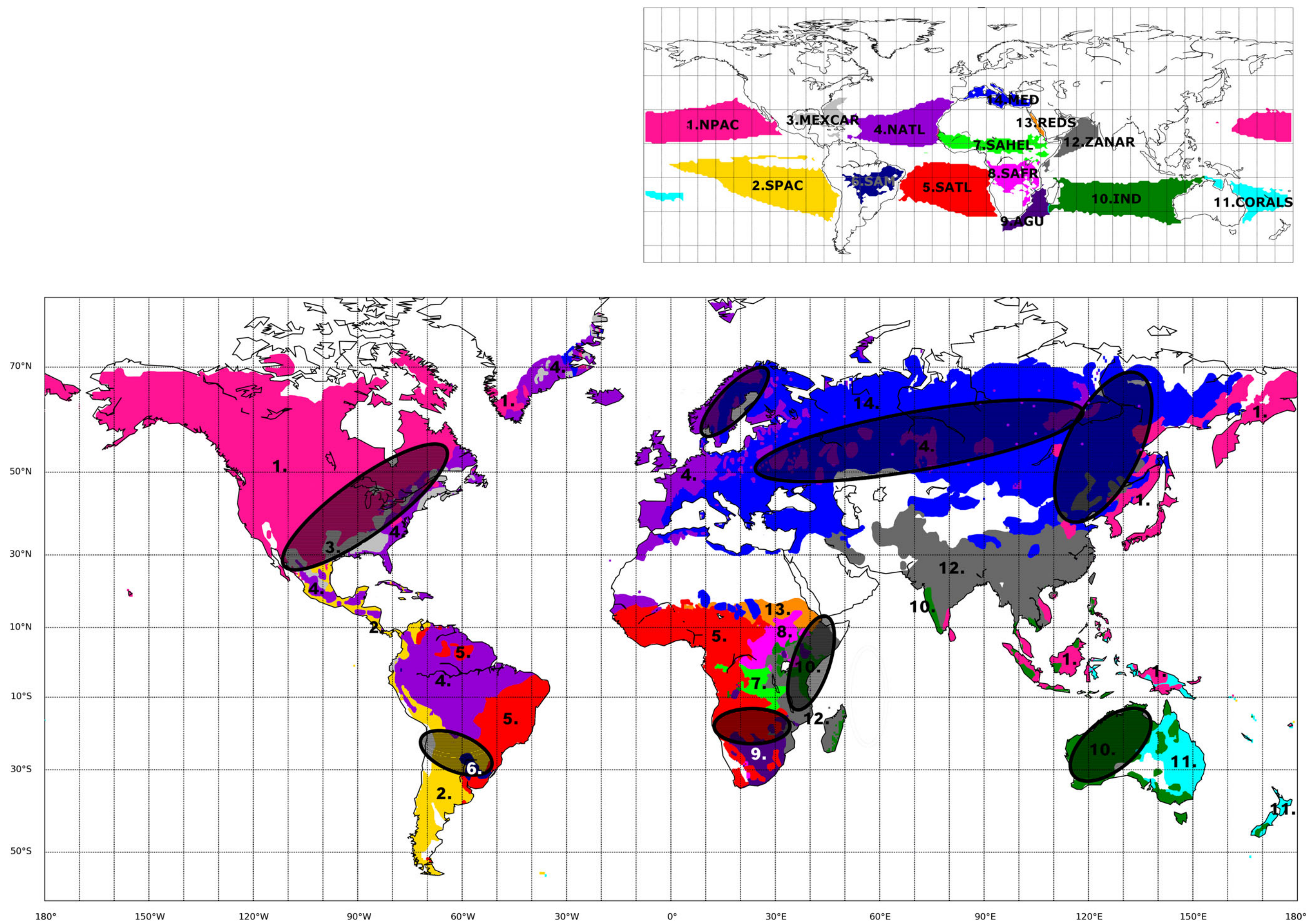

FIGURE 2 Main oceanic and terrestrial moisture sources and their area of higher moisture contribution associated with extreme precipitation events. The rounded areas represent the regions where the source of higher contribution changed compared with climatological mean precipitation. The sources defined are North and South Atlantic Ocean (NATL and SATL), North and South Pacific Ocean (NPAC and SPAC), Mediterranean and Red Seas (MED and REDS), Gulf of Mexico and Caribbean Sea (MEXCAR), Indian Ocean and Zanzibar Current and Arabian Sea (IND and ZANAR), Agulhas Current (AGU), South America (SAM), Sahel Region (SAHEL), and South Africa (SAFR).

different from the global climatological ones could be critical in the occurrence of precipitation. This is somewhat at odds with the decrease in precipitation as explained by the main global sources in extreme precipitation events compared with the climatological precipitation, the reduction being greater than 10% over most continental areas.

Considering the findings of Vázquez et al. (2020), individual analysis of extreme precipitation events over the different areas of the world would seem crucial in order to understand the local processes that occur. As an illustration, the Mediterranean and Atlantic moisture sources experience a redistribution of their influence over western Europe when extreme events occur. Vázquez et al. (2020) found penetration of moisture from the North Atlantic further east over the continent during extreme precipitation events in winter. This is in contrast to the stronger influence of this ocean during the western Mediterranean floods of 1982 as found by Insua-Costa et al. (2019) in comparison with the western Mediterranean (which shows a stronger influence over this area from a climatological point of view).

In this context, perhaps the most important challenge of the next few decades is to explore the specific characteristics of moisture transport associated with extreme precipitation and to understand more fully the mechanisms involved, especially in view of the importance of these events for the populations affected by them.

6.2 | Major mechanisms of moisture transport and extreme precipitation events

Different mechanisms are responsible from the moisture transport that produce extreme precipitation. Tropical and extratropical cyclones are linked to the occurrence of extreme precipitation events over several regions. For example, between 35% and 50% of the extreme 24 h precipitation over eastern North America, eastern Asia, or Japan is associated with tropical cyclones (Utsumi et al., 2017). Another mechanism of moisture transport causing extreme precipitation events is linked to the monsoonal circulations. This mechanism has important consequences over the regions that affects, and it is expected to be increased under global warming conditions (e.g., Lee et al., 2018; Zhang & Zhou, 2019). At local scale, land-atmospheric feedbacks are also critical in the occurrence of extreme precipitation. The convection associated with land-atmospheric feedbacks can highly influence the occurrence of extreme events (Diro et al., 2014; Guo et al., 2006; Lorenz et al., 2016). For example, at local scale, impacts of soil moisture on rainfall are relevant, especially in the transition zones between dry and wet areas (Guo et al., 2006).

Despite the variety of the mechanism involved in the occurrence of extreme precipitation, two of them are considered as the most important in terms of moisture transport, namely, Atmospheric Rivers (ARs) and Low-Level Jets (LLJs). In quantitative terms, the global transport of moisture is dominated mainly by these two meteorological phenomena (Gimeno et al., 2016). ARs are defined as elongated and narrow corridors through which large amounts of moisture are advected to extratropical latitudes mostly from (sub)tropical regions, whereas LLJs are wind corridors in which the maximum speed is found within the first km nearest the ground. LLJs are located mainly in tropical latitudes and are more localized than ARs in terms of their behavior than ARs. The two mechanisms are responsible for a significant portion of the meridional transport of moisture in the atmosphere, modulating regional and global patterns of precipitation on the continents. They thus play an important role in the availability of water resources, as well as in the maintenance of the current characteristics of the hydrological cycle. In fact, it is estimated that the transport of moisture from ARs alone represents more than 90% of the transport of the total flow of water vapor towards the poles at extratropical latitudes (Zhu & Newell, 1998).

LLJs cause maximum wind speeds in the lower troposphere, which is precisely where the maximum concentrations of water vapor are found. This explains why together with ARs LLJs are considered key drivers in the transport of vast amounts of water. These meteorological structures are well known to lead to precipitation events that could become "extreme" depending on the amount of water transported and their persistence. The link between LLJs and anomalous rainfall is documented in different regions such as the Great Plains (e.g., Harding & Snyder, 2015), South America (e.g., Vera et al., 2006), India (Viswanadhapalli et al., 2020), Africa (Vizy & Cook, 2019), or China (Du & Chen, 2019).

One of the best-documented LLJs on the Planet is the Great Plains Low-Level Jet (GPLLJ), which is responsible for the strong advection of moisture from the Gulf of Mexico and the Caribbean Sea to the eastern central United States (Algarra et al., 2019). It is estimated that one-third of the moisture that reaches landfall on the United States is carried by the GPLLJ (Helfand & Schubert, 1995; Higgins et al., 1997). Although the GPLLJ occurs throughout the year, it is more frequent and intense in the summer months and especially at night (Whiteman et al., 1997). Thus, any intensification of the GPLLJ is expected to be linked to increased precipitation in the western central United States. In fact, strong recurrent floods in this region are known to be linked with higher moisture transport as a consequence of the intensification of the GPLLJ (Barandiaran et al., 2013; Moore et al., 2012).

The South American LLJ (SALLJ) plays a major role in the distribution of rainfall in the South American continent. In general, the SALLJ penetrates the eastern margin of the South American continent, crossing the Amazon and diverting southwards through the Andes, transporting large amounts of moisture into the La Plata basin. Intensifications of the SALLJ have been linked to rainfall in this region (do Nascimento et al., 2016). Other relevant LLJs, although of secondary importance on the South American continent, are the Caribbean and Choco LLJs. The convergence of the two structures over western Colombia is well known in this region to contribute to the explanation of world-record rainfall (Poveda et al., 2014).

Monaghan et al. (2010) show a significant connection between the activity of NigthLLJs and nocturnal precipitation extremes in at least 10 regions of the world, including the Great Plains of the United States, Tibet, Northwest China, India, Southeast Asia, southeastern China, Argentina, Namibia, Botswana, and Ethiopia. Therefore, from the perspective of regional precipitation, LLJs are a focus of attention as a consequence of their importance for net moisture advection, and consequently for precipitation. Algarra (2019) identified the source and sink regions of moisture associated with LLJs on a global scale, showing enhanced evaporation in source regions when LLJs occur. Associated with global warming at a regional scale, enhanced peaks of rainfall and increased frequencies of GPLLJs are projected due to, among other factors, strengthening and westward displacements of the Atlantic subtropical anticyclone (Cook et al., 2008; Tang et al., 2017).

ARs are transient filamentary structures associated with enhanced transport of moisture from tropical and subtropical regions to extratropical latitudes. They feed warm conveyor belts, ahead of the cold front of extratropical cyclones, through enhanced water vapor transport in the lower troposphere (Ralph et al., 2018). The impact of ARs as precursors to extreme precipitation events and major floods is widely documented such as for the west coast of the United States (e.g., Dettinger, 2013; Dettinger et al., 2011), Europe (e.g., Eiras-Barca et al., 2021; Lavers & Villarini, 2013), and Chile (e.g., Viale et al., 2018). These meteorological structures are identified as the primary triggers of extreme precipitation events in these regions during the winter months. For example, it is estimated that ARs contribute quantitatively up to 50% of the annual precipitation seen in California (Ralph et al., 2018; Ralph & Dettinger, 2011; Rutz et al., 2014). Lavers and Villarini (2015) showed that ARs account for between 20% and 30% of the total precipitation in parts of Europe and the United States. A graphical summary of these results is displayed in Figure 3.

More recent studies have shown the positive effects of ARs on the hydroclimatology of these regions. This is in part due to their role in ending droughts (Dettinger, 2013), and also because it has been shown that in their milder versions they convey large amounts of nonextreme precipitation, which is necessary for the maintenance of the normal hydrological cycle (Eiras-Barca et al., 2021; Ralph et al., 2019).

The "force"—and therefore the risk of damage—of ARs will increase with the amount of water vapor carried by them, and with the increasing persistence of AR events (Ralph et al., 2019). Notwithstanding the plethora of mechanisms that lead to extreme precipitation through ARs, it is clear that orographic forcing is the main triggering factor for AR-related precipitation (e.g., Ralph et al., 2006; Smith et al., 2010).

Recent studies point to the more significant role of ARs in future climates (e.g., Espinoza et al., 2018; Payne et al., 2020). Considering the Clausius–Clapeyron scale, global warming is likely to bring about a wetter atmosphere and therefore a greater availability of water vapor in near-saturation transport events, inducing a greater advection of moisture by ARs. Algarra et al. (2020) report an increase in moisture content close to 7% for the period 1980–2017 in the sources of anomalous moisture uptake for ARs. Thus, in the context of global warming, any intensification of ARs due to the increased moisture contained in the structure means that the importance of ARs and thus the attention focused on them will increase, due to both their role in the maintenance of the hydrological cycle and to their socioeconomic impact.

6.3 | Future challenges

The proper understanding of weather and climate extremes is considered to be among the great challenges facing world climate research programmers. We now summarize the most pressing topics for future research.

Challenge 1: In recent decades, substantial progress has been made in the study of how global warming may affect extreme precipitation events. Despite this, there is still scope for improving the contextualization of the thermodynamic effect within the dynamic circulation, particularly at a local scale. Precipitation patterns will result from the interaction of the two mechanisms, which could help to explain the changes that take place.

Challenge 2: There is still substantial uncertainty inherent in the modeling of tropical extremes, which is related mostly to convection mechanisms. Some studies have estimated that the rate of increase of extreme tropical rainfall is

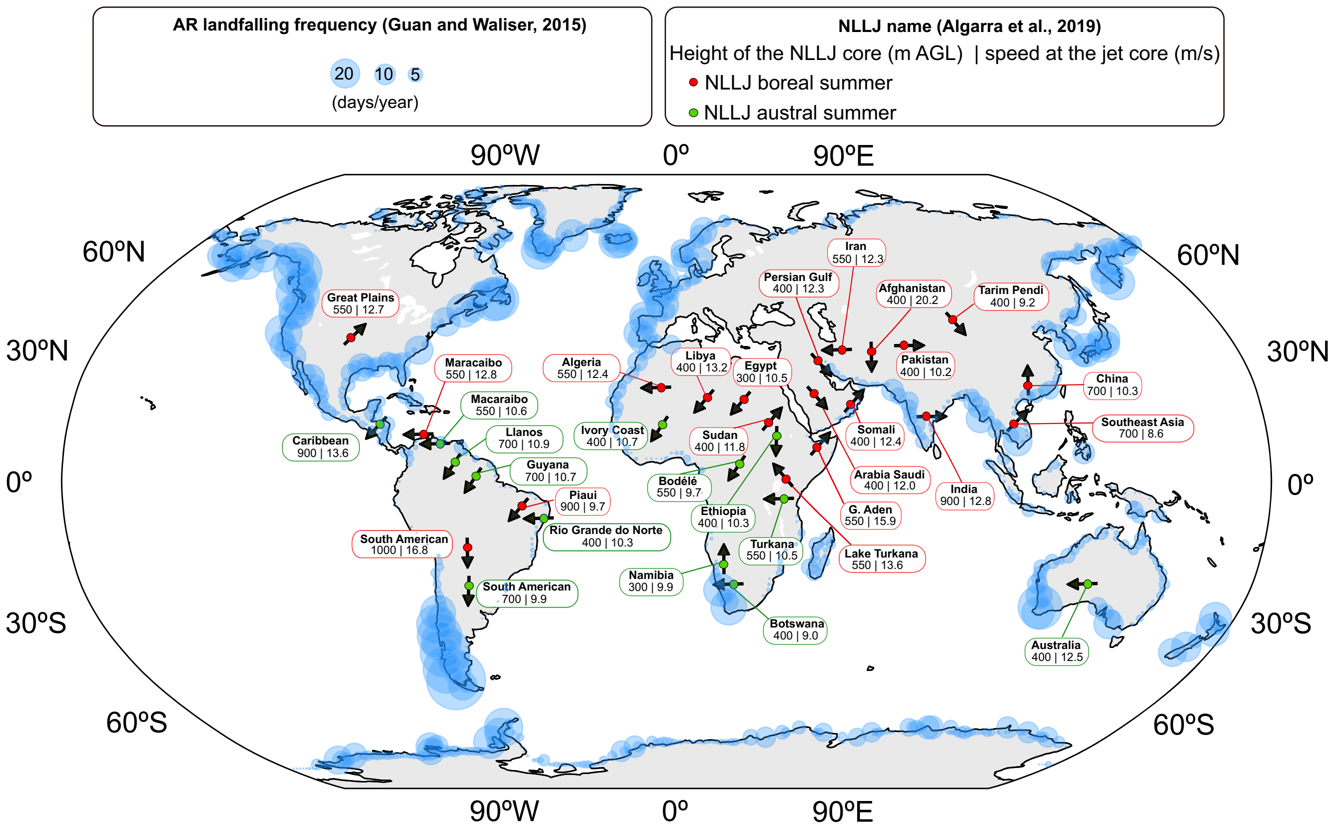

FIGURE 3 Location of the main moisture transport mechanisms at a global scale. The sizes of the blue circles reflect the landfall frequency of ARs (data from Guan & Waliser, 2015). The arrows indicate the direction of the Night LLJs (NLLJs) identified in Algarra (2019). The name of each NLLJ, height (in mgl) and speed (in mm/s) appears inside the colored boxes: Boreal summer NLLJs are in red and austral summer NLLJs are in green

increasing by around 10% per Kelvin (O'Gorman, 2012). Attempts to establish a clearer mechanistic understanding should therefore be a key focus for climate scientists.

Challenge 3: The estimated increase in the amount of expected atmospheric moisture content also suggests some kind of increase in precipitation. Moisture transport mechanisms will certainly play a major role in these potential changes in precipitation patterns. In particular, ARs and LLJs seem to have great potential in modulating these changes, as well as in the future availability of water resources. Despite significant improvements in the understanding of these mechanisms, substantial research is still required to improve the prediction of the behavior of the ARs and LLJs in the medium term. Understanding the changing characteristics essential to design mitigation and adaptation policies.

Challenge 4: The prediction of short- and long-term variability in time and space of extreme precipitation is a challenge of great interest in climate modeling and for studies of risk, both under current conditions and under projected continuous global warming. Models still simulate varying magnitudes of precipitation response to anthropogenic forcing, mostly due to the use of different schemes to parameterize at the subgrid scale. Not all parameterizations are appropriate in different contexts, and a consensus is needed to unify criteria and choose the most appropriate schemes.

Challenge 5: A better understanding and representation of the physical processes behind the convective mechanisms is needed, such as via the assimilation of water vapor flux data in model simulations, and enhanced resolutions and/or larger domain sizes are crucial to improve the simulation of extreme precipitation and its impacts (Guichard & Couvreux, 2017; Muller & Takayabu, 2020).

Challenge 6: A consensus, at least at regional scale, is required to achieve the best definition of the term "extreme" in order to establish the most accurate analysis of precipitation in this respect. There is a need to explore the different definitions of extremes and to establish the best procedures to use. This will allow more precise analysis and promote easier comparison between methods, as well as allowing an understanding of what is implied by the better characterization of these kinds of events.

Challenge 7: It is important to identify whether extreme events occur concurrently with other events (compound events), or whether intensification may be preceded by some additional factor that could help in their prediction (Zscheischler et al., 2018). A better understanding of compound events could improve the prediction of potentially high impact events.

Challenge 8: Given that a warmer environment could exacerbate extreme precipitation events, there is a clear need to improve robust techniques for the attribution of these changes to anthropogenic forcing, especially when they differ by region (Stott et al., 2016), and to minimize the uncertainties, with the aim of devising better predictive products to help society and decision-makers in the management of the risks associated with reducing vulnerability to extreme hydroclimatic events.

AUTHOR CONTRIBUTIONS

Luis Gimeno: Conceptualization (lead); funding acquisition (lead); supervision (equal); writing – original draft (equal); writing – review and editing (equal). **Rogert Sorí:** Methodology (equal); visualization (equal); writing – original draft (equal); writing – review and editing (equal). **Marta Vázquez:** Methodology (equal); visualization (equal); writing – original draft (equal); writing – review and editing (equal). **Milica Stojanovic:** Methodology (equal); visualization (equal); writing – original draft (equal); writing – review and editing (equal). **Iago Algarra:** Methodology (equal); visualization (equal); writing – original draft (equal). **Jorge Eiras-Barca:** Methodology (equal); visualization (equal); writing – original draft (equal); writing – review and editing (equal). **Luis Gimeno-Sotelo:** Methodology (equal); visualization (equal); writing – original draft (equal); writing – review and editing (equal). **Raquel Nieto:** Funding acquisition (lead); methodology (lead); supervision (equal); writing – original draft (equal); writing – review and editing (equal).

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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