climate

Review

Studies on Heavy Precipitation in Portugal: A Systematic Review

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Abstract: This systematic review, based on an adaptation of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement from 2020, focuses on studies of the atmospheric mechanisms underlying extreme precipitation events in mainland Portugal, as well as observed trends and projections. The 54 selected articles cover the period from 2000 to 2024, in which the most used keywords are "portugal" and "extreme precipitation". Of the 54, 23 analyse trends and climate projections of precipitation events, confirming a decrease in total annual precipitation, especially in autumn and spring, accompanied by an increase in the frequency and intensity of extreme precipitation events in autumn, spring and winter. Several articles (twelve) analyse the relationship between synoptic-scale circulation and heavy precipitation, using an atmospheric circulation types approach. Others (two) establish the link with teleconnection patterns, namely the North Atlantic Oscillation (NAO), and still others (three) explore the role of atmospheric rivers. Additionally, five articles focus on evaluating databases and Numerical Weather Prediction (NWP) models, and nine articles focus on precipitation-related extreme weather events, such as tornadoes, hail and lightning activity. Despite significant advances in the study of extreme precipitation events in Portugal, there is still a lack of studies on hourly or sub-hourly scales, which is critical to understanding mesoscale, short-lived events. Several studies show NWP models still have limitations in simulating extreme precipitation events, especially in complex orography areas. Therefore, a better understanding of such events is fundamental to promoting continuous improvements in operational weather forecasting and contributing to more reliable forecasts of such events in the future.

Keywords: extreme precipitation; atmospheric circulation types; NAO; atmospheric rivers; weather forecast; numerical weather prediction; thunderstorm; Portugal

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1. Introduction

The IPCC's (Intergovernmental Panel on Climate Change) Special Report on extreme events and disasters defines an extreme event as "the occurrence of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends (tails) of the range of observed values of the variable" [1]. However, some climate extremes (e.g., droughts, floods) may result from an accumulation of meteorological or climate events that, individually, are not considered extreme. Likewise, meteorological or climatic events, even if they are not extreme in statistical terms, can lead to extreme conditions or impacts, either by exceeding a critical threshold in a social, ecological or physical system or by occurring simultaneously with other events. Assessing the risk of extreme events is a matter of great importance due to the numerous negative impacts they can have on society, the economy and natural ecosystems [2,3].

Heavy precipitation is one of the main weather hazards, which can cause river floods, flash floods or landslides, and can seriously compromise human life, infrastructure, natural ecosystems, the agricultural and transport sectors and, consequently, the economy [3–7]. Although climate projections reveal an overall decrease in total annual precipitation in the Iberian Peninsula (IP), accompanied by a significant increase in dry spell lengths, increases in the frequency and intensity of heavy precipitation events are expected throughout the IP according to the Representative Concentration Pathways (RCP) scenario for the medium (2041–2070) and long (2071–2100) term periods [8,9]. The expected intensification of arid conditions will worsen the impacts of heavy precipitation events, e.g., by challenging water management and drainage infrastructure while favouring harmful surface runoff, surface water flooding and flash floods [10,11]. Hence, a better understanding of the potential impacts of extreme hydrometeorological events is needed, thus promoting more effective responses to their risks [12].

In particular, in mainland Portugal, located on the Atlantic-facing side of the IP, precipitation is strongly concentrated in autumn and winter [13–15], being mainly favoured by west/southwesterly air flows and extra-tropical cyclones that develop in the North Atlantic [13,16]. The intra- and interannual variability in precipitation in Western Iberia is strongly linked to the variability in large-scale atmospheric circulation systems [17,18], including the wave-breaking episodes of the sub-polar eddy-driven jet stream [19,20], or the state of the North Atlantic Oscillation (NAO), which play a critical role on winter precipitation over Western Iberia [21]. Additionally, the transport of moisture from the Atlantic Ocean to the continent, such as in the so-called atmospheric rivers (ARs), has been related to extreme precipitation events in Portugal. ARs have a greater influence between October and May [22]. Furthermore, precipitation in mainland Portugal is also strongly affected by the characteristics of the terrain [23,24], mainly northwards of the Tagus River (Figure 1), where the maximum average annual totals exceed 2000 mm in the northwest, contrasting with average values of less than 500 mm in the northeast, downstream of the main mountain ranges [14]. Moreover, in mainland Portugal, convective precipitation has a bimodal distribution [23], with peaks in April and October, being more pronounced in the northern hinterland, where lightning activity is also more frequent during these months [25]. This reveals the great importance of thermodynamic conditions (convective instability) and of mesoscale circulation (e.g., mountain circulations) in transition seasons.

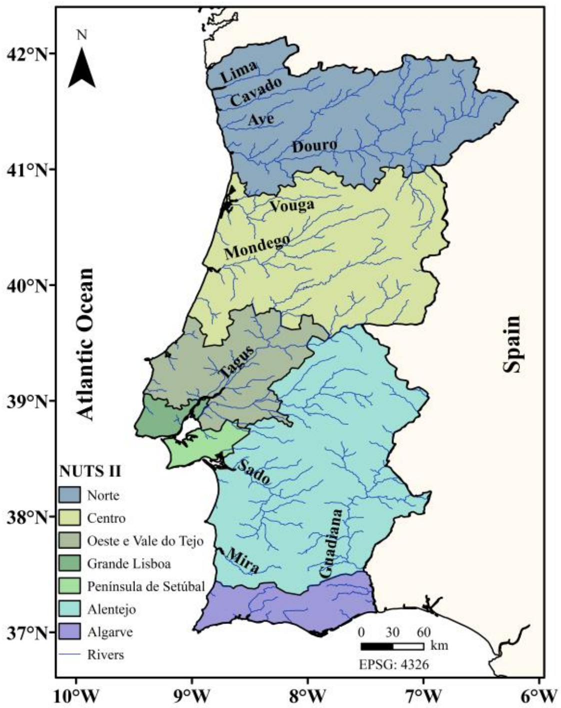

Figure 1. Map of the NUT II administrative divisions of mainland Portugal, and the main rivers.

Given the importance and complexity of this topic, the main objective of this research is to analyse the existing literature on the origin of extreme precipitation events in mainland Portugal. This systematic review aims to provide a comprehensive analysis of the physical mechanisms underlying the occurrence of extreme precipitation events in mainland Portugal. Furthermore, the different methods and indicators used in the analysis of this type of event will also be addressed, considering studies using observational evidence and modelling experiments. This study reviews the current state of research on heavy precipitation events in Portugal, allowing us to identify knowledge gaps in this area, promoting new research studies and providing useful information for more accurate weather forecasts and the reliable prediction of this type of event in the future.

In Section 2, the materials and methods used for the systematic review are described, based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) model [26]. In Section 3, the main results are presented and discussed, comprising the results from the bibliometric analysis, followed by a more detailed analysis of the selected articles. Finally, Section 4 summarises the main conclusions.

2. Materials and Methods

2.1. Methodology

The methodology used in this systematic review was performed following the guidelines of the most recent version of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) model (PRISMA 2020 abstract checklist in Table S1 and PRISMA 2020 checklist in Table S2) [26,27]. As suggested in this methodology, an initial protocol was created, comprising four fundamental phases, each contributing to a comprehensive and systematic examination of scientific publications, as illustrated in Figure 2. This allowed the consolidation of the guidelines and workflows that would be conducted throughout this study, obtaining consistent and accurate results.

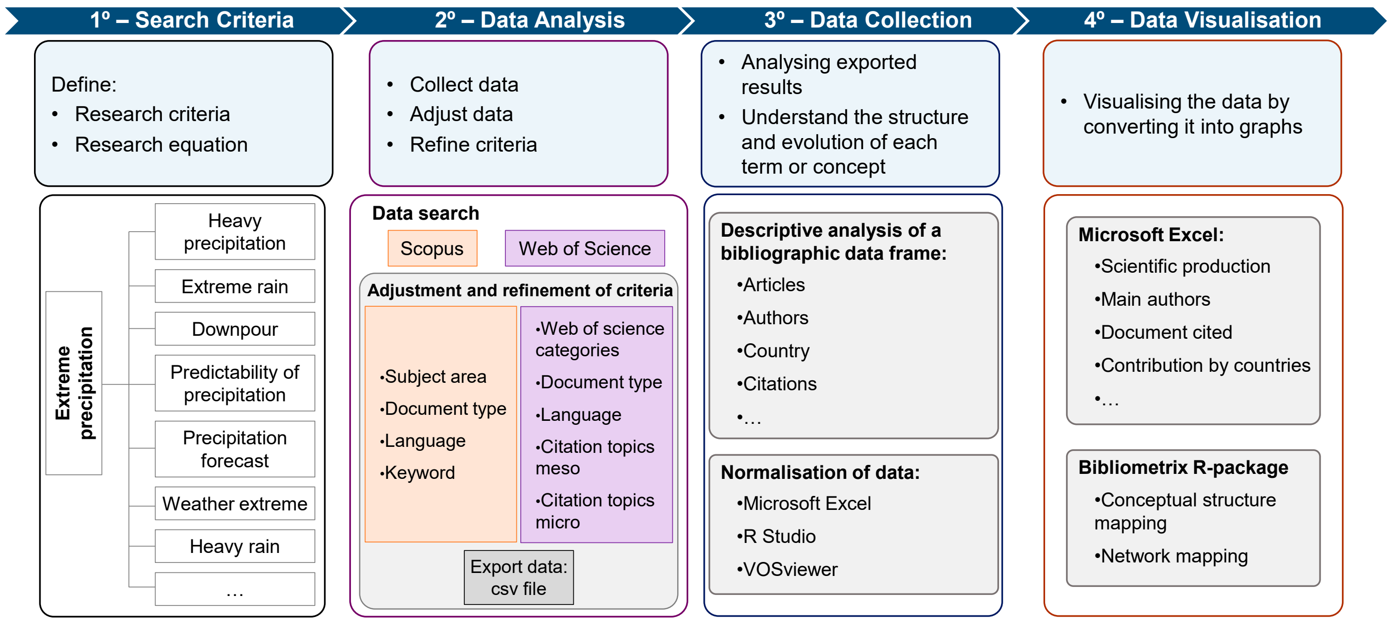

Figure 2. Scheme of the methodology applied in the current systematic literature review.

The first step, Search Criteria, in addition to determining the main topic of this review, "risk assessment of heavy precipitation events in Portugal", also allowed the establishment of more specific research parameters, such as selecting keywords. This selection guarantees the selection of studies relevant to the present study.

The second step, Data Analysis, comprised accessing publications that meet pre-established parameters. To ensure the accuracy and integrity of the dataset, this process involved several iterative adjustments and refinements. Duplicate and irrelevant entries were removed to preserve data integrity and ensure that only relevant publications were considered in the analysis.

The Data Collection (third step) began by applying criteria to exclude articles based on title and abstract that did not meet the pre-defined criteria. After this exclusion, an analysis of the selected articles was performed to identify trends, patterns and relationships in the literature.

Lastly, the Data Visualisation step facilitated the interpretation of the results. The analysed data were visualised using specialised software tools, the Bibliometrix R-package version 4.2.3 and VOSviewer version 1.6.20, allowing data summaries and visualisation through network maps, co-authorship networks and bibliographic coupling diagrams. This allowed an understanding of relationships and intricate patterns within the dataset [28].

2.1.1. Defining Search Criteria

This study analyses the existing literature on the risk assessment of intense precipitation events in Portugal, starting with their driving physical mechanisms. The main keywords were identified and clustered into two categories to achieve this goal. The first category was related to extreme events, mainly focusing on extreme precipitation events. It included keywords such as "heavy precipitation", "heavy rain", "extreme precipitation", "extreme rain*", "intense precipitation", "intense rain*", "torrential rain*", "torrential precipitation", "downpour", "severe rain*", "severe precipitation", "hail*", "thunder*", "weather extreme*", "extreme weather", "flood", "flash flood*", "nwp", "numerical weather prediction", "arome", "ecmwf", "precipitation forecast*", "weather forecast*", "weather prediction", "wrf", "predictability of precipitation" and "predictability of moist convection". The second category was related to the target area and included keywords such as "portugal" and "portuguese". The asterisk (*) represents one or more unspecified characters in a search term, allowing for flexible and broad matching. Search platforms typically use lowercase letters for keywords to ensure consistency and maximise the retrieval of relevant results, as capitalisation variations (e.g., "Portugal" vs. "portugal") could otherwise exclude some sources.

2.1.2. Data Compilation

Different online platforms offer access to academic databases and scientific research search engines. The Scopus (https://www.scopus.com, accessed on 26 April 2024) and Web of Science (WoS) (https://www.webofscience.com, accessed on 26 April 2024) platforms were chosen, which are the most commonly used literature search engines by researchers in different areas of Earth sciences. They allowed access to basic information about the publications, including identification of the source (such as journal or document, year of publication, volume and page), the name of the author, the institution or institutional address, references, the type of document, title, keywords, abstract and subject.

The advanced search query string also enables the use of complex search queries by incorporating field codes and Boolean operators to narrow down the search scope. Boolean operators within the query string link different search terms, while proximity operators help locate words that are near or within a specified distance from one another [28]. For the research process in both databases, the Boolean operator connector 'OR' was initially used. This ensures that at least one of the specified terms (e.g., "heavy precipitation" OR "heavy rain" OR "extreme precipitation" OR "extreme rain*") appears in the search results. As stated in the previous section, an "*" at the end of the word root was also used to retrieve suffix variations, which allows plurals and linguistic variants to be included in the search results. Subsequently, the Boolean operator 'AND' was used to further refine the search, ensuring that the retrieved documents contained at least one of the terms cited, together with the study area ("portugal"). These measures contributed to honing and concentrating the research, guaranteeing the collection of pertinent and trustworthy data related to the topic under study.

2.1.3. Adjustment and Refinement of Criteria

To guarantee precision, a strict process was put in place, utilising specific inclusion and exclusion criteria for each research platform. Every term underwent a detailed review, concentrating on the titles of research articles, abstracts and keywords. Due to the prevalent use of English in academia, only articles published in English-language journals were taken into account.

To enhance the search effectiveness, specific adjustments and refinements were made to narrow down the query string, as detailed in Table S3. These changes aimed to pinpoint articles that fulfilled the study criteria regarding concepts of extreme events in Portugal.

2.1.4. Export and Analysis of Data

The data obtained from Scopus and WoS were exported in CSV format (comma-separated value), which contains bibliographic information, titles, abstracts, keywords and other relevant details. However, it is essential to recognise that information obtained from bibliographic sources can contain inaccuracies, necessitating a data verification process, which was carried out by a manual review of author names, journal titles and affiliations and the detection of duplicate articles.

2.2. Bibliographic Source Assay

According to the methodology described in the previous section, a bibliographical consultation was carried out for the last time on 26 April 2024 in the Scopus and WoS databases, applying the search criteria equation shown in Table 1. Nevertheless, to reduce the potential for bias, searches across both platforms were conducted independently, ensuring that the process was thorough and consistent across different stages of the review. This approach aimed to enhance the reliability of the search results by mitigating individual biases and increasing the comprehensiveness of the evidence identified.

Table 1. Databases and queries were used to define the parameters of this systematic review.

Database	Query
Scopus (accessed on 26 April 2024)	TITLE-ABS-KEY(flood* OR "flash flood*" OR "heavy precipitation" OR "heavy rain" OR "extreme precipitation" OR "extreme rain*" OR "intense precipitation" OR "intense rain*" OR "torrential rain*" OR "torrential precipitation" OR downpour OR "severe rain*" OR "severe precipitation" OR hail* OR thunder* OR "weather extreme*" OR "extreme weather" OR nwp OR "numerical weather prediction" OR arome OR ecmwf OR "precipitation forecast*" OR "weather forecast*" OR "weather prediction" OR wrf OR "predictability of precipitation" OR "predictability of moist convection") AND TITLE-ABS-KEY(portugal OR portuguese)
Web of Science (accessed on 26 April 2024)	TS = (flood* OR "flash flood*" OR "heavy precipitation" OR "heavy rain" OR "extreme precipitation" OR "extreme rain*" OR "intense precipitation" OR "intense rain*" OR "torrential rain*" OR "torrential precipitation" OR downpour OR "severe rain*" OR "severe precipitation" OR hail* OR thunder* OR "weather extreme*" OR "extreme weather" OR nwp OR "numerical weather prediction" OR arome OR ecmwf OR "precipitation forecast*" OR "weather forecast*" OR "weather prediction" OR wrf OR "predictability of precipitation" OR "predictability of moist convection") AND TS = (portugal OR portuguese)

The final dataset comprised 2578 publications, with 1461 obtained from Scopus and 1117 from WoS. Before the initial screening, by title and abstract, 1686 articles were excluded using the selection criteria presented in the Supplementary Materials (Table S3). In addition, 75 duplicate articles were also identified. By analysing the title and abstract, 711 and 36 articles were removed, respectively, eventually leaving 52 articles in total. A complementary search resulted in the addition of two articles to the analysis. Therefore, the methodology applied yielded 54 articles for the subsequent analysis. All information is shown in the PRISMA diagram illustrated in Figure 3.

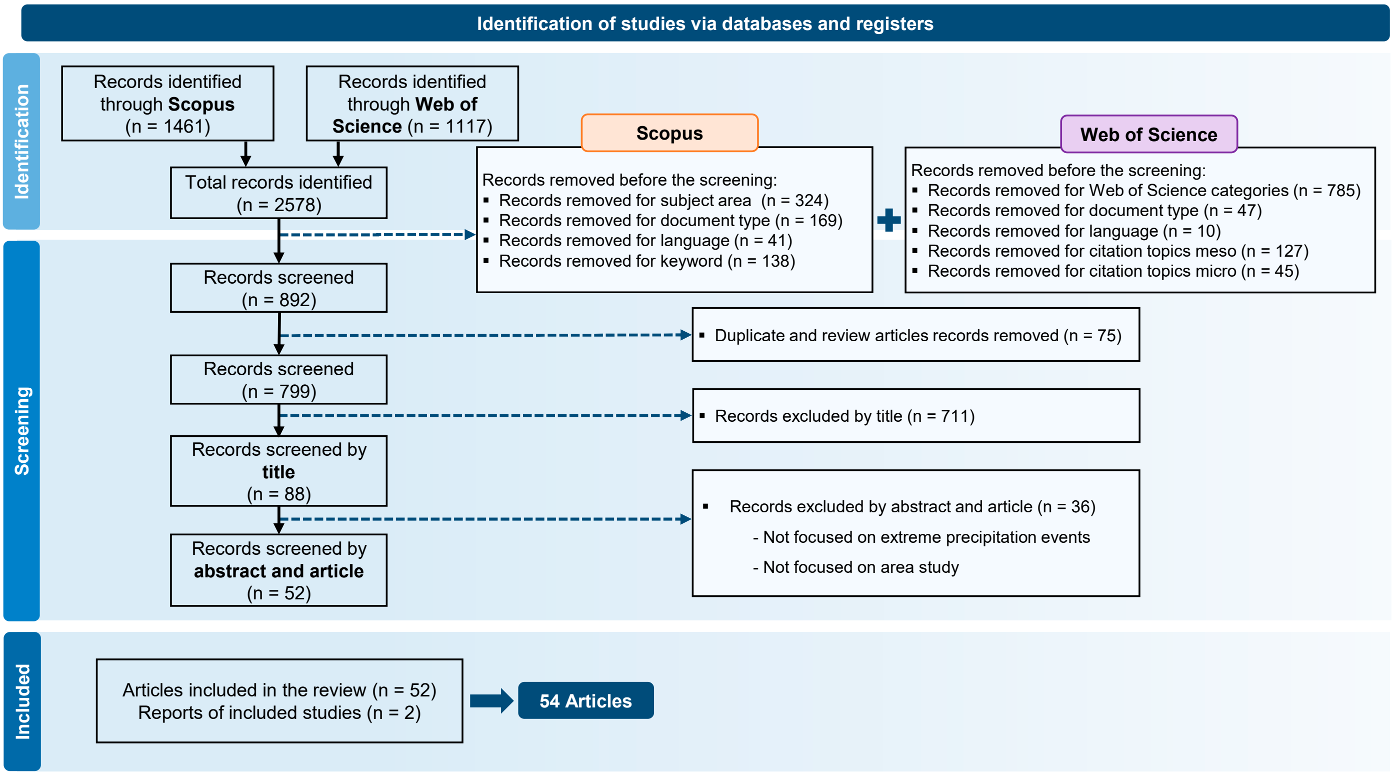

Figure 3. PRISMA flow diagram of the systematic literature review search adapted from [29].

Analysis of Articles Review

Initially, Section 3.2.1 presents a definition of the terms heavy and extreme precipitation, which is important for understanding the different terminologies used in the selected studies and for standardising the terms throughout the other sections, ensuring coherence and comparability throughout the review.

Based on the screening of the articles, they were classified into four groups, each with a different focus: observed changes and future projections (Section 3.2.2), large-scale circulation patterns (Section 3.2.3), modelling heavy precipitation events (Section 3.2.4) and other extreme events (Section 3.2.5). The articles analysed in Section 3.2.2 (Table S4) include 23 studies aimed at identifying trends, variations and climate change projections of extreme precipitation events. Section 3.2.3 (see Table S5) primarily focuses on large-scale atmospheric patterns that contribute to extreme precipitation events in Portugal, with 17 articles being identified. The subsequent section, Section 3.2.4, comprises 5 articles (see Table S6) that evaluate different databases and the performance of Numerical Weather Prediction (NWP) models in simulating heavy and extreme precipitation events. Given that heavy precipitation events are often associated with thunderstorms [30], which can lead to other weather hazards such as tornadoes, heavy hailstorms and intense lightning activity, Section 3.2.5 also covers these extreme meteorological events. Understanding these events can provide insights into compound events at a regional scale, for which 9 articles were identified (see Table S7).

3. Results

3.1. Bibliometric Analysis

The main information from the bibliometric analysis carried out regarding extreme precipitation events' occurrence in Portugal is presented in Table 2.

Table 2. Main information about overall selected articles.

Description	Results
Main information about data:	
Timespan	2000:2024
Sources (journals, books, etc.)	28
Documents	54
Document average age	9
Average citations per doc	44.8
References	2867
Document contents:	
KeyWords Plus (ID)	425
Author's Keywords (DE)	156
Authors:	
Authors	137
Authors of single-authored docs	1
Authors' collaboration:	
Single-authored docs	1
Co-authors per doc	4.2
International co-authorships %	27.8
Document types:	
Article	54

With 28 sources and 54 documents, it is clear that this topic is of high importance. The average number of citations per document (44.8) demonstrates the high impact and recognition of this topic by the scientific community. Moreover, the average age of the documents (9 years) shows that the awareness of the relevance of this subject has been increasing in recent years. Furthermore, the relatively high number of references (2867) highlights the breadth of the literature drawn on by researchers. The presence of 425 unique KeyWords Plus (ID) and 156 unique Author's Keywords (DE) reflects the diverse research topics and areas of focus within this topic. The collaboration level is also important, as evidenced by the average of 4.2 co-authors per document and the significant percentage (27.8%) of international co-authorships. Of the 54 studies selected, 46 were conducted in affiliated Portuguese Institutional Units (Table S8), which is expected given that this review focuses on heavy precipitation events in the country. Spain ranks second with three studies in affiliated Spanish Institutional Units, reflecting its geographical proximity and similar climatic conditions.

The distribution of the number of publications per year, between 2000 and 2024, is shown in Figure 4. The annual numbers reflect the year-on-year increase in publications, whereas the cumulative totals represent the overall accumulation of research documents throughout the specified period. Over the period under analysis, there was a significant variation in the number of articles published per year, with an increase in the number of publications from 2012 onwards, coinciding with the launch of a special report by the IPCC entitled "Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation" [1], showing growing interest for this research topic. The cumulative total of published articles on extreme precipitation events in Portugal reveals significant changes in the focus of research over the past years, characterised by an inconsistent rate of increase.

The 54 selected documents were analysed using the co-occurrence analysis function of VOSviewer. From these articles, an author keyword co-occurrence network was created by identifying the keywords and developing a matrix with VOSviewer. The authors provided 156 keywords, all appearing at least once, for mapping in VOSviewer. Among these keywords, all 156 (100%) were used at least once, with 27 keywords (17.3%) used twice and 12 keywords (7.7%) used three times, as detailed in Table 3.

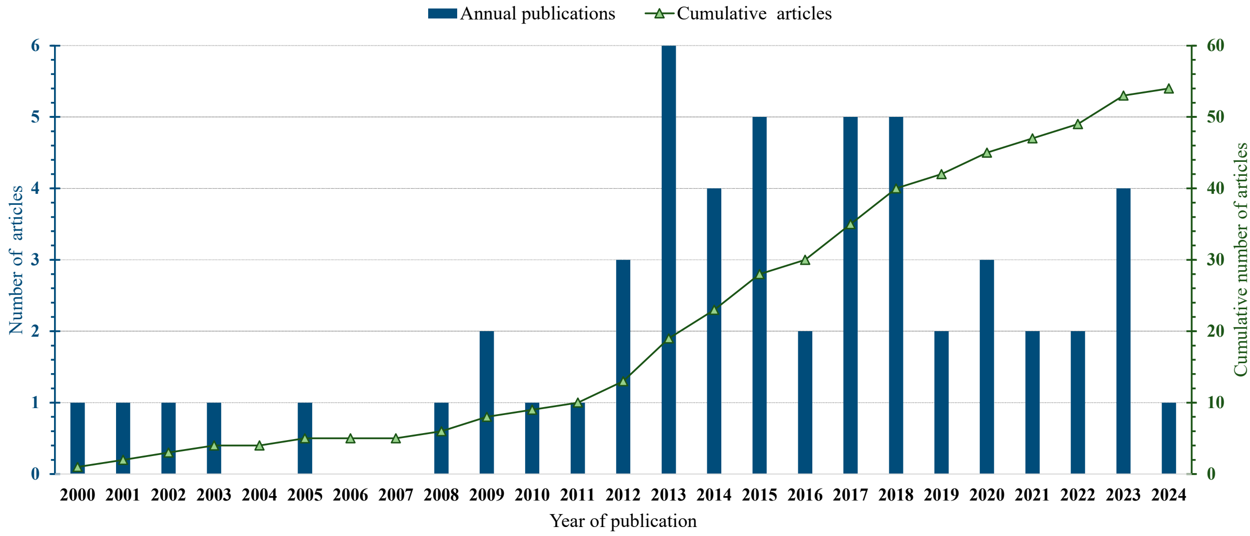

Figure 4. Temporal distribution of articles included in the systematic review by publication year.

Table 3. Minimum number of occurrences of Author's Keywords (DE).

Minimum Number of Occurrences	1	2	3	4	5
Keywords meet threshold	156	27	12	9	6
Occurrences use (%)	100	17.3	7.7	5.8	3.8

Figure 5 illustrates the author's keyword co-occurrence network, where the size of each node corresponds to the frequency of use of a specific keyword. This bibliometric map was created based on a minimum occurrence limit of two keywords. The visualisation of these relationships unfolds through a network comprising 27 keywords (Table 4), which are categorised into six distinct clusters, as illustrated in Figure 5.

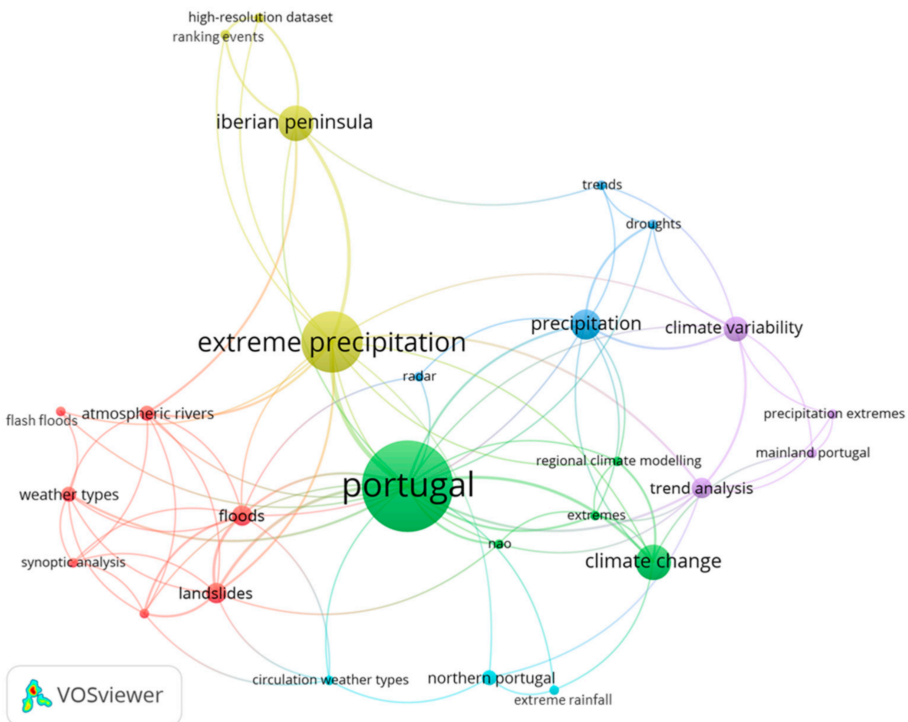

Figure 5. Constructed Author's Keywords (DE) co-occurrence network, used at least twice, using VOSviewer.

The keywords most used (Table 4) in these studies are "portugal" and "extreme precipitation", with 18 and 12 occurrences, respectively. The remaining terms focus especially on meteorological and hydrological phenomena (precipitation; floods; flash floods; landslides), climate change and trends ("climate change"; "climate variability"; "trends"; "trend analysis"; "stochastic simulation"; "synoptic analysis"; "ranking events"), atmospheric patterns ("weather types"; "circulation weather types"; "space–time patterns"; "nao"; "atmospheric rivers") and also the base of data and forecasting tools ("arome"; radar; "disaster database"; "high-resolution dataset"; "regional climate modelling").

Table 4. The number of occurrences of Author's Keywords (DE), used at least twice, and total link strength.

Keywords	Occurrences	Total Link Strength
portugal	18	34
extreme precipitation	12	25
climate change	7	10
iberian peninsula	7	12
precipitation	6	12
climate variability	5	10
floods	4	14
landslides	4	15
trend analysis	4	11
atmospheric rivers	3	10
northern portugal	3	4
weather types	3	8
circulation weather types	2	5
disaster database	2	9
droughts	2	5
extreme rainfall	2	3
extremes	2	7
flash floods	2	3
high-resolution dataset	2	5
mainland portugal	2	4
nao	2	6
precipitation extremes	2	3
radar	2	3
ranking events	2	5
regional climate modelling	2	6
synoptic analysis	2	5
trends	2	4

3.2. Articles Review

3.2.1. Definition of Heavy Precipitation Events

Precipitation events are commonly defined as events when the precipitation amount exceeds 1 mm per day [31]. These events are classified by intensity and duration and can occur on different temporal and spatial scales [14]. Due to the significant variation in precipitation patterns worldwide, it is impractical to establish a universal definition for the term "extreme precipitation event" that would apply to all regions [32]. The "Guidelines on the Definition and Characterization of Extreme Weather and Climate Events" [32] recommends the use of indices based on local climatological conditions to objectively characterise an extreme rainfall event. However, within the scientific community, there is still considerable uncertainty about the best method to characterise extreme and heavy precipitation events. A precipitation event may be considered extreme, according to one of the following criteria: (1) it has a significant impact (for instance, floods, casualties); (2) the precipitation exceeds a fixed threshold over a specific time interval (sub-hourly, hourly, 6-h, or daily); (3) it is considered extreme due to its rarity, based on either a percentile (95th or 99th percentile) threshold or its return period (100 years or more).

In the present study, the term "heavy" will be applied when referring to absolute, quantitative thresholds, indicating predefined limits. Conversely, the term "extreme" will be used in the statistical context, and thresholds are defined relative to data distributions, using percentiles (Rainfall Rate (RR) above 95 ptile or 99 ptile), as presented in Table 5, in line with the studies referred to in the table. This table also presents the criteria used by the Portuguese Weather Service (Instituto Português do Mar e da Atmosfera—IPMA—https://www.ipma.pt/en/index.html, accessed on 10 August 2024) to issue meteorological warnings for precipitation. These criteria are based on hourly and 6 h accumulations. The yellow and orange warnings refer, respectively, to heavy and very heavy precipitation events. According to MeteoAlarm, a red warning should be issued when the weather is very dangerous and major damage and accidents are likely to occur (https://www.meteoalarm.org/en/live/page/_legend, accessed on 10 August 2024). Thus, these events are considered extreme, and the thresholds defined were chosen by the IPMA due to their rarity and expected impacts. MeteoAlarm is an Early Warning Dissemination System that visualises, aggregates and accessibly provides awareness of information from 38 European national meteorological and hydrological services.

Table 5. Criteria used in literature to define extreme and heavy precipitation events in Portugal.

Type of Event	Time Scale		Threshold	References
Precipitation	Daily		Precipitation $\geq$ 1 mm	[33,34]
Heavy or extreme Precipitation	Daily		Precipitation $\geq$ 20 mm (Heavy)	[33–40]
			Precipitation $\geq$ 25 or $\geq$30 mm (Very Heavy)	[34,37,41–45]
			RR > 95 ptile or >99 ptile (Extreme)	[34,35,37,38,40,41,45,46]
	Sub-daily *	1 h	10 $\leq$ Precipitation $\leq$ 20 mm (Heavy)	[14]
			20 < Precipitation $\leq$ 40 mm (Very Heavy)	
			Precipitation > 40 mm (Extreme)	
		6 h	30 $\leq$ Precipitation $\leq$ 40 mm (Heavy)	[14]
			40 < Precipitation $\leq$ 60 mm (Very Heavy)	
			Precipitation > 60 mm (Extreme)	
	Sub-hourly	10 min	Precipitation $\geq$ 5 mm (Heavy)	[14,47]

* Criteria for issuing precipitation warnings according to IPMA, using thresholds based on hourly and 6 h accumulations. The heavy events refer to the yellow warning, very heavy and extreme events refer to the orange and red warnings, respectively.

3.2.2. Observed Changes and Future Projections

Several studies analysed the long-term trends of heavy and extreme precipitation events, four covering the IP [35,48–50], eleven mainland Portugal [34,36–39,41,46,51–54] and eight its regions [33,40,42–45,55,56], providing a more detailed and regionalised view of the spatial and temporal trends of these events (Table 6).

Table 6. Summary of main findings observed in mainland Portugal, and references, for the observed trends of precipitation and heavy precipitation events.

		Findings	References
Precipitation	Annual Autumn Spring	Decrease	[34,36–39,41,46,51–54] [36,41,46,52,53]
Heavy Precipitation	Autumn Spring Winter	Increase	[34,35,37,39,41] [46] [35,46]

For the IP, while Refs. [35,48] focus their work on analysing long-term precipitation trends, Refs. [49,50] present methods to classify precipitation events. Initially, in [48], the period 1903–2003 highlights an increase in rainy days in most meteorological stations, except in the western region of Portugal and the Gulf of Cádiz. For the analysed sub-periods (1903–1953 and 1954–2003), the opposite behaviour was observed for autumn and spring. In the first sub-period [48], a decrease in the number of precipitation days was found, especially in autumn, contrasting with the second sub-period, in which there was an increase. In turn, in spring an increase in the number of days of precipitation occurred in the first sub-period, with a decrease occurring in the second sub-period analysed. Bartolomeu et al., 2016 [35] present extreme precipitation trends for a shorter period (between 1986 and 2005), using observational data from the network of meteorological stations from the Iberian Peninsula and WRF (Weather Research and Forecasting) simulations driven by the ERA-Interim reanalysis. This study reveals a positive trend in the R95pTOT index (the sum of precipitation in days where daily precipitation exceeds the 95th percentile of daily precipitation in the baseline period) for the northern region of Portugal, at the annual timescale. Seasonally, a negative trend of the consecutive wet days (CWD) index in the south of the IP in the summer and a positive trend of the R75p (number of days when the total amount of precipitation is above the 75th percentile) in the north of Portugal in the spring were observed.

Regarding the classification of precipitation events, Ref. [49] developed a method to classify daily precipitation events, considering their intensity (normalised precipitation departures from the seasonal climatology) and the corresponding affected area, classifying the different regions of the IP, from 1950 to 2008. Ramos et al., 2014 [49] highlight the event of 5 November 1997, which occurred due to a cut-off low that caused 11 deaths in Portugal and 21 in Spain. Also, Ref. [50] developed a method to classify extreme precipitation episodes considering different timescales between 2 and 10 days, and the affected areas.

Several studies have already documented changes in the amount and regimes of precipitation. In general, these studies show a decrease in total annual precipitation [34,36,41,46,51–54] and a higher contribution of extreme precipitation. Of note is an increase in the frequency and intensity of precipitation extremes, seen from trends between 1941 and 2007 [34,41] and for projections between 2071 and 2100 [46], and a greater influence of the North Atlantic Oscillation (NAO) on the variability in precipitation in mainland Portugal [34]. The NAO is the main mode of variability in sea level pressure in the North Atlantic Ocean. The spatial pattern of the NAO consists of a dipole, with an approximate north/south orientation, with one of the centres located over Iceland and the other extending through the mid-latitudes of the North Atlantic and centred around 35° N, near the Azores, presenting two phases [57]. The positive phase of the NAO is characterised by a deep depression over Iceland accompanied by a strong anticyclone in the Azores, responsible for dry conditions in Southern European countries [58] and daily positive temperature anomalies in the IP [21]. The negative phase of the NAO is characterised by a weak depression over Iceland accompanied by a weak anticyclone in the Azores, allowing extra-tropical cyclones to travel over the IP [58,59]. Several previous studies showed a clear relationship between mainland Portugal's precipitation variability and the NAO [21,60–62].

Although a decrease in total annual precipitation is expected under climate change [37,52] between historical (1941–2007) and future scenarios (A1B SRES, 2071–2100), an increase in daily precipitation intensity is projected, with these extreme events presenting a greater contribution to the total annual precipitation for the 2046–2065 period [39] and future projections throughout the 21st century (RCP2.6, RCP4.5 and RCP8.5) [51]. Seasonally, several studies point to a precipitation decrease in the transition seasons [36,41,46,52,53], i.e., spring and autumn, for similar periods to those previously mentioned. The opposite occurs for extreme precipitation events, where an increase in these events is expected in autumn [34,41], spring and winter [46]. To understand the regions of Portugal most susceptible to this type of event, [38] developed an extreme precipitation susceptibility index (EPSI). This study examines the EPSI between 1950 and 2003, revealing the greater susceptibility of the southern coast and the northern and central mountainous regions. On the other hand, the areas of lowest susceptibility are in the northeastern municipalities and along the central–western coast. These results are similar for the autumn and winter seasons, with an increase in susceptibility in the Lisbon region during spring. In summer, an increase is expected in the northeast region, and a decrease in the southern regions, with no significant differences observed in autumn and winter. These changes in precipitation patterns could accentuate the difference between the north, typically more humid, and the south, more arid [54].

Several studies were developed for more specific regions in mainland Portugal. For the northern region, [45] analysed the spatial and temporal variability in heavy and extreme precipitation indices from four indices: total precipitation on rainy days, with daily precipitation $\geq$ 1 mm (PRCPTOT); number of days with precipitation amount $\geq$ 30 mm (R30); the maximum 5-day precipitation amount (R $\times$ 5 day); and total precipitation amount $\geq$ 95th percentile (R95p). Annually, [45] verified a decrease in these indices for the 1955–1999 period. Seasonally, heavy (R30) and extreme (R95p) precipitation rates tended to decrease in winter, spring and summer in over 80% of the precipitation series. The opposite was observed in autumn; the four indices studied showed that over 70% of the series showed a positive trend. To develop a climate adaptation framework to identify effective climate change measures, [33] used the WRF model to calculate future projections with a high level of spatial resolution. These simulations showed a tendency towards an increase in extreme weather events associated with an increase in temperature and annual precipitation.

As for the southern region, all studies [42–44] show a tendency towards an increase in the intensity and frequency of heavy precipitation events in the second half of the 20th century, with impacts on the management of environmental risks, such as soil erosion and desertification. The spatial analysis of heavy precipitation events has revealed greater homogeneity and spatial continuity in recent decades [43,44]. A study developed for the Lisbon Metropolitan Area [55], for the period from 1864 to 2021, also showed an increase in the frequency and intensity of extreme precipitation events, reaching rainfall of up to 120 mm in just one day.

As already mentioned, the impacts of climate change are a global concern; however, at a regional scale, these impacts can be especially severe, significantly affecting a region's socioeconomic activities. In Portugal, an example of this is viticulture, in which atmospheric conditions have enormous relevance to growth and productivity. Two studies analysed climate impacts in Protected Denomination of Origin (PDO) regions in mainland Portugal, one for all regions [40] and another exclusively for the PDO regions of the north [56]. Fonseca et al., 2023 [40], from the calculation of seventeen indices of climatic extremes for the regions/sub-regions of designation of origin of Portuguese wine, for the historical period (1981–2010) and future periods (2041–2070 and 2071–2100), verified an increase in temperature extremes in all the wine-growing regions of Portugal, particularly in the westernmost regions. For precipitation extremes, there was a decrease in future periods, accompanied by a generalised decrease in precipitation. On the other hand, Ref. [56] assessed the probability of unprecedented precipitation totals in spring and harvest seasons over the wine-growing regions of Northern Portugal. This study reveals that seasonal precipitation totals considerably greater than any observed are possible in the current climate, and yet an unprecedented precipitation event in different seasons could occur with a probability between 1% and 5% in the current climate.

3.2.3. Links to Synoptic-Scale Circulation Patterns

Several studies were developed to analyse the interactions between synoptic-scale circulation patterns and extreme meteorological events. Different studies evaluated the North Atlantic Oscillation (NAO) influence on precipitation events [63,64]. Using data from weather stations for the period 1958–1997, Ref. [63] showed that changes in precipitation are linked to different types of synoptic-scale circulation, with significant influences from the Atlantic and Mediterranean, highlighting a strong correlation between the NAO and precipitation, especially in winter and spring. In the winter, this study highlights the strong influence of air masses from the West and Southwest Atlantic over a large part of the Peninsula, and the north and northwest surface flow over the north/northwest of Spain. In turn, Ref. [64] evaluated the impact of the NAO on winter precipitation, relating these episodes to landslides. It showed that the precipitation composite corresponding to the positive phase of the NAO presents a relatively low median value (47 mm/month) when compared to the negative phase of the NAO (134 mm/month). Thus, for the negative phase of the NAO, there is a greater probability of the occurrence of long-lasting rain episodes, and therefore a greater probability of large landslide events.

In addition to understanding the influence of the NAO on extreme events and precipitation, several studies [22,65] were focused on understanding the role played by atmospheric rivers (ARs) in extreme precipitation events. According to the definition of the *Glossary of Meteorology* of the American Meteorological Society, ARs correspond to a long, narrow and transient corridor of strong horizontal water vapour transport that is typically associated with a low-level jet stream ahead of the cold front of an extra-tropical cyclone [66–68]. The large amount of water vapour that is transported by ARs can lead to heavy precipitation events and flooding, in which they are forced upward, for example by mountains or by ascent in the warm conveyor belt [69].

The detection of ARs can be carried out based on the use of the vertically integrated horizontal water vapour transport (IVT) between 1000 and 300 hPa, as in [70]. These authors evaluated the implementation of the integrated vapour transport extreme forecast index (IVT EFI) when compared with the precipitation EFI (extreme forecast index), in discriminating extreme precipitation events in the Iberian Peninsula. The IVT EFI was shown to have slightly more skill (than the precipitation EFI) in discriminating extreme precipitation anomalies across the Western Iberian Peninsula (Portugal and Northwestern Spain) from forecast day 11 onwards. The IVT EFI showed a more accurate prediction of the location of extreme events further in advance than the EFI. However, for short-term forecasts, the EFI has proven to be more effective.

Considering the intensity of precipitation and the affected area, Ref. [65] found that the association between ARs and extreme days of precipitation is more significant in the western domains (Portugal, Minho, Tagus and Douro) than in the eastern and southern regions. In turn, using the PT02 and SP02 databases, Ref. [22] showed that there is a relationship between atmospheric rivers and extreme precipitation days in Portugal, especially during April, May and September. Ramos et al., 2018 [22] also showed that the impacts of atmospheric rivers are considerably higher for the most significant events in Portugal, decreasing when considering days with less intense precipitation

Given the complexity of understanding extreme precipitation events, several studies have analysed the relationship between different types of atmospheric circulation patterns and the occurrence of this type of event. For this purpose, several Atmospheric Circulation Types (ACTs), also referred to in the literature as Circulation Weather Types (CWTs), were defined and studied [5,6,10,16,71,72]. The cyclonic (C) ACT is characterised by a depression centred west of the IP, sometimes accompanied by a blocking anticyclone located between Iceland and the British Isles, triggering westerly–southwesterly winds over Iberia. The anticyclonic (A) ACT is characterised by a high-pressure system centred over the Iberian Peninsula, extending to the Azores and North Africa. The dual-anticyclonic (AA) regime is characterised by two high-pressure systems, one corresponding to the Azores high and another located over Central Europe [6]. The easterly (E) ACT is characterised by an anticyclone over the British Isles, driving easterly winds over the IP, and is generally associated with dry and warm weather in summer and colder weather in winter in Iberia. The southwesterly (SW) ACT is characterised by a weakening of the Azores anticyclone and a deep low near the Gulf of Biscay, promoting southwesterly winds, generally associated with rainy weather in Western Iberia. The westerly (W) ACT is characterised by the predominance of a high-pressure system at approximately 30° N (from the Azores to North

Africa) and a low-pressure centre near the British Isles. The northwesterly (NW) ACT is characterised by the presence of a strong Azores high extending to the Madeira Islands and a low-pressure system centred southeast of the British Isles, resembling the positive phase of the NAO. The southeasterly (SE) ACT is characterised by low-pressure regions extending from Madeira to the Azores Islands and anticyclones over northwestern Europe, promoting southeast winds (dry winds) to the IP. The southerly (S) ACT is characterised by a low-pressure system northeast of the Azores, and by high pressure over Central Europe, with southerly winds over the western region of the IP.

For the IP, Ref. [71] analysed the relationship between the circulation types and the frequency of precipitation heaviness and extremes (>90th percentile) in spring and autumn in 44 stations. This study reveals that, in the western and southern regions, heavy and extreme precipitation days decrease in spring, mainly due to a decrease in the southwestern cyclonic flow, generally associated with the passage of cold fronts and the greater transport of wet air from the Atlantic towards mainland Portugal. On the other hand, the patterns associated with heavy and extreme precipitation (mainly the northwest flow) are more frequent in autumn, contributing to more extremes in stations located in the central and northwestern regions of the IP.

In turn, Refs. [5,10] focused their analysis on mainland Portugal. Based on the identification of 131 flood episodes, Ref. [5] showed that the cyclonic (C) ACT is strongly associated with days of sudden flooding in the northern basins. This type of pattern features deep low-pressure systems northwest of Iberia, stronger than average for this ACT. For the southern basins, the C type still presented the highest relevance for flood occurrence, but to a lesser extent, since the easterly wind (E) and dual-anticyclonic (AA) ACTs also acquired some importance. The AA ACT events are generally characterised by atypical largely zonal troughs extending towards Portugal, while the E ACT events hint at the occurrence of anomalously strong cut-off low systems over Southern Iberia. Pereira et al., 2018 [10], for the period 1865–2015, verified that in the central and northern regions of Portugal, extreme precipitation events are mostly driven by southwesterly (SW), westerly (W), northwesterly (NW) and cyclonic (c) ACTs. In the southern part of the country, the circulation ACTs with a southern and eastern component (easterly (E), southeasterly (SE) and southerly (S)) are the main drivers of extreme events, results also confirmed in [72]. A monthly and seasonal analysis carried out by [6] for the northern region of Portugal revealed that anticyclonic (A) and easterly (E) ACTs are more common in winter, while the ridge (R) regime prevails in the summer. The results also highlight that the C ACT, more frequent in late autumn and winter, is largely related to floods. In contrast, A and E regimes are predominant in summer, when thunderstorms and heavy precipitation episodes are linked to mesoscale systems.

Using sub-hourly precipitation data from weather stations, Refs. [14,47] carried out an analysis of the different dynamic and thermodynamic mechanisms that are at the origin of sub-hourly heavy precipitation events (SHHPs) in mainland Portugal. Santos and Belo-Pereira, 2022 [14] performed their analysis based on two synoptic regimes, remote (RemL) and regional (RegL) low-pressure systems. The first (RemL) is characterised by a deep low-pressure core westward of the British Isles, accompanied by a strong meridional trough, reflecting the presence of cold fronts propagating over mainland Portugal. The second (RegL), is characterised by a low-pressure system just westward of Iberia, accompanied by a high-pressure belt with a maximum over the British Isles, a clear signature of mid-latitude blocking highs and inverted dipolar structures over Western Europe and the adjacent North Atlantic. These studies reveal that RegL SHHPs show two marked maxima in spring and autumn, while RemL SHHPs show a single maximum in autumn. Their daily distribution shows that, under the influence of RegL, most heavy precipitation events occur in the afternoon/evening. On the other hand, for REmL regimes, SHHP events are spread more uniformly throughout the day.

In turn, Ref. [47] focused on RegL events for the period from 2000 to 2022, showing that heavy precipitation events in mainland Portugal are associated with the presence of a depression just west of the IP with a cold core, particularly strong at medium levels, and a positive vorticity anomaly, strongest in the upper troposphere, extending downwards to low levels, a typical characteristic of cut-off lows. These conditions drive differential positive vorticity advection and thus the upward motion eastward of the low. These systems also promote atmospheric instability and humidity advection at low levels, favouring the occurrence of heavy precipitation over Western Iberia.

Different case studies were carried out to understand extreme precipitation events. Initially, Ref. [73] analysed the event that occurred on the 25th and 26th of November 1967, which was characterised by strong convection, fuelled by humid air over the Lisbon region associated with a low-pressure system centred near Lisbon. On the other hand, the analysis of the events that occurred in the period from 5 to 16 February 1979, analysed by [74], shows that the atmospheric circulation that was at the origin of these precipitation events was dominated by "wet" conditions, typical of cyclonic (C), westerly (W) or southwesterly (SW) circulation ACTs. More recently, the event that occurred on 1 November 2015 in the Algarve (southern coast), was analysed by [75], who applied the radar–rain gauge fusion method to improve the precipitation fields, leading to a reduction in errors in precipitation estimations. The environment associated with the passage of three extra-tropical cyclones that affected Portugal was analysed in [76]. This study showed that the convergence of humidity, the high water vapour content and unstable atmospheric conditions associated with these depressions favoured the occurrence of large amounts of precipitation in mainland Portugal.

3.2.4. Modelling Heavy Precipitation Events

Different studies focus their attention on evaluating different databases [77] and the performance of Numerical Weather Prediction (NWP) models [78–81].

To assess uncertainty in precipitation products, Ref. [77] used Frequent Rainfall Observations on the GridS (FROGS) database during two atmospheric river events. This presented some limitations, especially for precipitation products based on satellite data, individually or combined with other products, which were the poorest at capturing the daily precipitation over land in Portugal. Nevertheless, the reanalysis data and the gauge-based products showed the best agreement with local ground stations. However, all model products showed a general underestimation of the total precipitation.

Different studies revealed the existence of a positive correlation between precipitable water vapour (PWV) and precipitation. Anomalously high water vapour content before and during events of extreme precipitation was identified, but not all PWV peaks led to extreme precipitation. In this way, Ref. [78] analysed a simple algorithm to classify the time evolution of the PWV signal on a single GPS (Global Positioning System) station and to identify conditions favourable for triggering heavy precipitation in the Lisbon region. The results indicated relevant information in the signal, at least concerning the probability of the precipitation occurrence of most rain events, as almost all the severe rainfall cases were well predicted. However, it also had some limitations, such as a large fraction of false alarm forecasts.

Ferreira et al., 2014 [79] used the WRF model to simulate the extreme event that occurred on 18 February 2008 to test different physical parameterisations. The results showed that the combination of cumulus and microphysics schemes is of high importance in predicting precipitation amounts. Furthermore, [79] also showed that a small change in the domain resolution has a stronger impact on the spatial precipitation patterns than on the predicted amounts.

Different models and parameterisations were tested by [80,81] to simulate heavy precipitation events. Initially, Ref. [80] simulated the atmospheric conditions associated with the heavy precipitation episode observed in mainland Portugal on 11 and 13 March 2002, using the Regional Atmospheric Modelling System (RAMS). The results showed that the RAMS model is effective in describing the precipitation patterns, although it fails to accurately predict the precipitation amount. Furthermore, the model showed a tendency to overestimate the areas of heavy precipitation. In turn, Ref. [81] evaluated the performance of the WRF model in simulating spatial and temporal patterns for a complex orographic region in North–Central Portugal. They tested three model initiation methods, which showed a similar performance and proved to be less accurate for stations located in rugged terrain and deep valleys.

3.2.5. Other Extreme Events

In addition to extreme precipitation events, other extreme weather phenomena, such as lightning, hail and strong wind gusts, are often linked to precipitation events, since the underlying physical mechanisms are commonly similar [82]. By studying these phenomena together, it is possible to obtain valuable insights about their interactions, impacts and life cycles.

Different studies highlight the temporal and spatial analysis of cloud-to-ground (CG) lightning [83–85]. Soriano et al., 2001 [83] focuses on the relationship between convective precipitation and cloud-to-ground lightning, showing a higher correlation coefficient for semi-arid areas (0.75) than for humid regions (0.65). Studies [84,85], exploring the interannual and seasonal variability of cloud-to-ground lightning, identified specific patterns of lightning activity in different seasons and regions, showing a greater activity of electrical discharges in the period from May to September (71%), with a bimodal distribution that peaks in May and September, with most lightning activity recorded in the afternoon. In spring and autumn, lightning activity spreads throughout the country, while it concentrates more over Northeastern Portugal in summer. In winter, Portugal generally experiences low lightning activity. Furthermore, [85] showed that CG flashes are mainly located over high-altitude areas in late spring and summer, while they tend to occur in coastal areas in autumn.

The influence of dynamic factors on the occurrence of lightning was also analysed by [24,85]. Santos et al., 2013 [85] identified three possible factors to justify the distribution of lightning in the IP: (1) storms orographically forced over mountainous areas, mainly from May to September, (2) tropospheric buoyancy forcing over the central–western regions and north in summer and over the Mediterranean regions in autumn, and (3) near-surface thermal contrasts from October to February. From three lightning regimes for Portugal (WREG: winter regional regime, WREM: winter remote regime, SREG: summer regional regime), [24] showed that the difference in the equivalent potential temperature in the 700–500 hPa layer is the best predictor for the three regimes.

Campos et al., 2024 [86] evaluated the performance of the ECMWF (European Centre for Medium-Range Weather Forecasts) model in forecasting lightning during the fire season, showing a temporal lag, in which the model predicts the onset and cessation of lightning activity too early.

Another atmospheric phenomenon identified in this systematic review concerns tornadoes, as they are generated by convective storms. Leitão, 2003, and Leitao and Pinto, 2020 [87,88] analysed the meteorological conditions behind the occurrence of tornadoes in Portugal, and their periods of occurrence. The 27 events documented by [87] occurred mainly from October to December, in association with strong cold fronts or line storms, with most cases associated with deep extra-tropical cyclones westwards of the IP. Summertime tornadoes had their genesis in strong convective cells and mesoscale convective systems favoured by the strong diurnal heating, being less dependent on the synoptic conditions. Also [88], analysing a larger number of events, showed that tornadoes over Portugal were more frequent from October to December and in March, being consistent with the distribution of thunderstorms [25]. The most intense tornadoes (F3) were generated by supercells, but a large proportion of weaker, shorter-lived tornadoes were associated with quasi-linear convective systems (QLCSs). These QLCSs can also lead to heavy precipitation, as observed on 23 December 2009 in southern Portugal, where a bow echo line, triggered by an upper cold front, produced rainfall amounts of more than 11 mm in 10 min [89].

On 7 December 2010, an F3 tornado produced an exceptionally long (for the Portugal climatology) damage path of around 54 km [90]. This tornado was spawned by a convective storm with typical supercell characteristics, which produced large hail cores and intense lightning, with a predominance of cloud-to-ground discharges, before the tornado's touchdown, accompanied by intra-cloud discharges during its existence.

It is also worth mentioning one article about hail events in Portugal [23]. This provides a climatology of hail in mainland Portugal, using 39 years of synoptic observations and analyses of their relationships with thunderstorms and convective precipitation. It was possible to conclude that hail events are more common in Northern Portugal during late winter and early spring, favoured by upper-level troughs/lows [23]. Some stations of the interior also register a secondary peak in the autumn (October).

4. Summary

The present study provides a comprehensive analysis of the physical mechanisms underlying heavy and extreme precipitation events in mainland Portugal, exploring the trends and indicators of these events, based on studies that analysed trends, variability at different timescales, and climate projections of extreme precipitation events. On the seasonal scale, different studies show a decrease in precipitation during the transition seasons (spring and autumn) [36,41,46,52,53], accompanied by an increase in extreme precipitation events in autumn [34,41], spring and winter [46]. Spatially, the regions of the southern coast and the mountainous regions of the north and centre are more susceptible to the occurrence of extreme precipitation events, while the central–western coast tends to be less susceptible [38]. These spatial variations are strongly affected by terrain characteristics (orographic forcing) in the northern and central regions. Moreover, it is expected that the difference in annual precipitation values between the north, generally more humid, and the south, more arid, will become more pronounced [54].

Different studies have analysed the connection between atmospheric circulation types and the occurrence of heavy and extreme precipitation events, mostly at daily or monthly timescales. For this purpose, some studies establish the link between NAO phases and seasonal precipitation, based on the daily [63] and monthly total precipitation [64]. These studies showed that during the negative phase of the NAO, when extra-tropical cyclones travelling to Iberia are more prevalent, there is a greater probability of the occurrence of long-lasting rain episodes in Western Iberia, mainly in the winter wet season.

Other studies relate the different ACTs with extreme precipitation events [5,6,10,16,71,72]. Seasonally, these studies show that the anticyclonic type (A) is the most frequent weather pattern throughout the year, except during the summer months, frequently dominated by the northeasterly (NE) and northern (N) ACTs. The cyclonic (C) ACT is also present throughout the year, reaching a maximum value during spring, in accordance with the maximum frequency of Atlantic blocking episodes [16]. In winter, there is a high degree of association between the wettest ACTs (C, W and SW) and winter precipitation.

In the northern and central regions of Portugal, flash floods and landslides associated with heavy precipitation events are favoured by strong westerly (SW, W and NW) and cyclonic (C) ACTs [5,6,10], indicating the highest prevalence of cyclonic ACTs [5]. Seasonally, during spring and autumn, between 1946 and 1990, a decrease in the relative importance of precipitation associated with the SW and W ACTs, and an increase in the relative importance of rainfall associated with the NW and C ACTs was identified [16]. These regions are generally affected by extra-tropical cyclones northwestwards of the Iberian Peninsula [10]. In the southern region of Portugal, the dual-anticyclonic (AA) and easterly (E) ACTs are generally associated with flash flood events [5,10], especially in autumn, the season in which there is a greater occurrence of heavy precipitation events [72], with an increase in the influence of the N and SE regimes [16]. Generally, this precipitation is associated with cut-off lows, located in the vicinity of the Gulf of Cádiz [10,72].

Furthermore, changes in ACTs frequency explain the interannual variability in heavy and extreme precipitation days (R90p) [71], in which a lower (higher) frequency of SW (NW) ACTs is associated with a negative (positive) trend of R90p in spring (autumn). The interannual variability in drier years is generally characterised by very low values of the combined frequency of the wettest ACTs (C, W and SW), with a predominance of a strong Azores high, which restricts the number of depressions and frontal systems that affect Portugal [16]. The same conclusion can be drawn for the wettest years, which present the highest values of the combined wettest ACT frequency.

Using sub-hourly precipitation observations [47], it was shown that heavy precipitation events in Portugal are associated with low-pressure systems located in the northwest of Iberia, that is, with the typical characteristics of the cyclonic ACT (C), with a greater predominance in the negative phase of the NAO. Furthermore, the association between ARs and days of extreme precipitation is more significant in the western regions of the IP, such as Portugal [65]. The intensity of AR impacts was greater for more significant events, mainly during April, May and September [22].

Different numerical prediction models, such as WRF [79,81] and RAMS [80] have been used to simulate extreme precipitation events. Although different physical parameterisations have been tested, they present major limitations in reproducing the intensity of precipitation events, overestimating or underestimating the observed values. Despite a greater difficulty in predicting the intensity of precipitation occurrence, the WRF model presented better results in predicting periods of occurrence. The horizontal model resolution proved to be one of the main limitations in simulating this type of event, especially in regions with a complex orography, with the RAMS model underestimating precipitation amounts at higher elevation areas.

Concerning other extreme weather events, the studies on cloud-to-ground lightning highlight the relationship between that and convective precipitation [83–85]. They show a stronger correlation in the inner and more continental areas of the country [83]. The interannual and diurnal variability in cloud-to-ground lightning showed greater activity between May and September, being more frequent in the afternoon. In summer, there is higher activity in Northeastern Portugal, while in spring and autumn, it tends to be more widespread, with winter eventually showing less activity. Strong activity is felt at higher elevations in spring and summer [84,85]. This distribution can be justified through three dynamic factors: orographic storms, tropospheric buoyancy forcing and thermal contrasts close to the surface. The occurrence of tornadoes in Portugal was also revised, showing that they tend to occur mainly from October to December, associated with convective cells driven by extra-tropical cyclones and mostly by cold fronts. On the contrary, summer tornados are very rare and are associated with strong convective cells and mesoscale convective systems, triggered by mesoscale circulations [87,88]. Regarding hail fall events, they are more frequent in the north of the country in late winter and early spring, in association with upper-level lows/troughs. Some stations of the interior also reveal a secondary peak in autumn (October) [23].

5. Conclusions

The bibliometric analysis of extreme precipitation events in Portugal reveals the high relevance of this topic of research, as evidenced by 28 sources and 54 documents. Between 2000 and 2024, there was a significant variation in the number of annual publications, with a peak in 2013, indicating a growing interest in the topic since 2012. A keyword co-occurrence analysis identified 156 keywords, forming six distinct clusters, with "portugal" and "extreme precipitation" presenting greater relevance in the present study.

The studies addressed here show that climate trends and projections indicate a reduction in total annual precipitation, particularly during the autumn and spring. Furthermore, there is an expected rise in both the frequency and intensity of extreme precipitation events, especially in autumn, spring and winter.

Although substantial progress has been made in studying extreme precipitation events in Portugal, research at hourly or sub-hourly scales remains limited. This is crucial for better understanding mesoscale, short-duration events. Different studies indicate that Numerical Weather Prediction (NWP) models continue to face challenges in accurately simulating extreme precipitation, particularly in regions with complex terrain. Therefore, it is necessary to gain a better understanding of such events to minimise risks across various socioeconomic sectors, such as in viticulture [91], a key agrarian chain in Portugal that is particularly vulnerable to their occurrences. To achieve this, continuous improvements in operational weather forecasting are essential, providing valuable information for more accurate weather predictions and ensuring a more reliable forecasting of such events in the future.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/cli12100163/s1, Table S1. PRISMA 2020 for the abstract checklist. Table S2. PRISMA 2020 checklist. Table S3. Selection criteria applied on research platforms. Table S4. Articles selected for the analysis of observed changes and future projections. Table S5. Articles selected for the analysis of large-scale atmospheric patterns. Table S6. Articles selected for the evaluation of different databases and the performance of Numerical Weather Prediction (NWP) models. Table S7. Articles selected for the analysis of other extreme events. Table S8. Summary of the number of studies conducted by country.

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