



Impact of extreme rainfall events on landslide activity in Portugal under climate change scenarios

Abstract Rainfall is considered the most important physical process for landslide triggering in Portugal. It is expected that changes in the precipitation regimes in the region, as a direct consequence of climate change, will have influence in the occurrence of extreme rainfall events that will be more frequently, throughout the century. The aim of this study relied on the assessment of the projected future changes in the extreme precipitation over Portugal mainland and quantifying the correlation between extreme rainfall events and landslide events through Rainfall Triggering Thresholds (RTTs). This methodology was applied for two specific locations within two Portuguese areas of great geomorphological interest. To analyze the past frequency of landslide events, we resorted to the DISASTER database. To evaluate the possible projected changes in the extreme precipitation, we used the Iberia02 dataset and the EURO-CORDEX models' runs at a 0.11° spatial resolution. It was analyzed the models' performance to simulate extreme values in the precipitation series. The simulated precipitation relied on RCM-GCM models' runs, from EURO-CORDEX, and a multimodel ensemble mean. The extreme precipitation assessment relied on the values associated to the highest percentiles, and to the values associated to the RTTs' percentiles. To evaluate the possible future changes of the precipitation series, both at the most representative percentiles and RTTs' percentiles, a comparison was made between the simulated values from EURO-CORDEX historical runs (1971–2000) and the simulated values from EURO-CORDEX future runs (2071–2100), considering two concentration scenarios: RCP 4.5 and RCP 8.5. In the models' performance, the multimodel ensemble mean appeared to be within the best representing models. As for the projected changes in the extreme precipitation for the end of the century, when following the RCP 4.5 scenario, most models projected an increase in the extreme values, whereas, when following the RCP 8.5 scenario, most models projected a decrease in the extreme values.

Keywords Climate change · Extreme precipitation · Landslide events · Portugal · Regional climate modelling

Introduction

Landslides can cause negative impact on society including in transportation and communication networks but also inducing human casualties and property losses (e.g., Pereira et al. 2018), and affect agriculture (Santos et al. 2019). Some reviews, like Guha-Sapir et al. (2012) and IPCC (2012), have pointed that these hydro-geomorphological events have been increasing throughout the last century, and it is expected to further raise as a direct consequence

of climate change. Global warming is expected to increase the frequency and intensity of severe rainfall events, a primary trigger of rapid-moving landslides that cause many landslide fatalities (Gariano et al. 2017).

Moreover, Gariano et al. (2017) conducted an extensive review of studies focused on the impacts of climate change on landslides and acknowledged a wide range of issues, such as the course of the changes in the stability conditions, the location, abundance, frequency, and type of landslides in response to the projected climate changes. In other words, the impact of climate change on landslides occurrence (or lack of occurrence) still needs further investigation; however, its relationship with the rainfall regime is often emphasized. Segoni et al. (2016) stressed the importance of analyzing the changing trends in rainfall and consequently the regular updating of regional rainfall thresholds to be considered for the triggering of landslides. Furthermore, based on projected variations in rainfall conditions at regional scale, Alvioli et al. (2018) also highlighted that precipitation thresholds for landslide occurrence are expected to change.

In Portugal, the most important physical process for landslide triggering is extreme rainfall (Zêzere et al. 2015; Vaz and Zêzere 2016). Despite the meteorological factors that trigger these events, the anthropogenic factors, like increasing population worldwide, urbanization in hazardous areas, deforestation, and land use change, amplify the negative consequences, therefore increasing the exposure of people and infrastructures to disaster risk (Tavares et al. 2012; Promper et al. 2015; Gariano et al. 2017). A way of managing this risk relies on the development of natural disaster databases that highlights the relationship between the occurrence of these events and the exposed and vulnerable population (Pereira et al. 2018). Zêzere et al. (2014) developed a unique database with information on past floods and landslides that caused human casualties in Portugal, the DISASTER database, which was later updated by Pereira et al. (2018). The latter authors narrowed this database records to circa 130 hydro-geomorphological events, in Portugal, over the past century, of which 67 events have had landslides. The DISASTER database only considers hydro-geomorphological events that produced human consequences, such as fatalities, injuries, missing, displaced, and/or homeless people (Pereira et al. 2018). This database will be used as a baseline tool in this study for the assessment of damaging landslide activity over Portugal mainland.

To assess the relationship between rainfall events and the occurrence of landslide events, empirical methods of linear regression were developed. These establish a link between the amount of accumulated precipitation and the consecutive days of accumulated

precipitation — Rainfall Triggering Thresholds (RTTs). The thresholds were obtained at the local scale and translate the amount and duration of precipitation that, when reached or exceeded, may induce a landslide event (Reichenbach et al. 1998; Guzzetti et al. 2007). Landslide events can occur whether a rainfall event is intense but lasts a few days or being less intense, but lasting longer duration periods. Therefore, by taking into account possible future climate change scenarios of precipitation, it is possible to project (considering the RTT) the future changes in the frequency of these rainfall-induced events.

To evaluate changes of atmospheric variables, like precipitation, dynamical downscaling methods like regional climate models (RCMs) are used. The RCMs are forced in their boundaries by general circulation model (GCM) results. Despite their continuous improvement, and the fact that these models can reproduce fairly well the large-scale patterns of many important fields, current GCMs still have a coarse resolution (~50 to 100 km) and fail in representing regional to local scale processes and variables (Giorgi, 1990; Giorgi and Mearns 1991, 1999; Soares et al. 2012a). Therefore, GCMs are used as forcing models to RCMs for local impact studies, since RCMs have a much finer resolution of circa 10 km (Leung et al. 2003; Laprise 2008; Wang et al. 2004; IPCC 2018). Four pathways, referred as Representative Concentration Pathways (RCPs), were developed, considering that the radiative forcing levels increase to 8.5, 6, 4.5, and 2.6 W/m², until the year 2100, relative to pre-industrial levels (van Vuuren et al. 2011; Meinshausen et al. 2011; Soares et al. 2017).

Many scientific studies resort to RCMs forced by GCMs, that run forced by greenhouse gases concentration scenarios, to evaluate changes of local and regional climate under distinct climate change scenarios. According to the state-of-the-art modelling studies, it is projected that climate change will cause an increase in the frequency of the intense rainfall events over southern Europe and, therefore, an increase in the occurrence of hydro-geomorphological disasters (IPCC 2021).

Soares et al. (2017) studied the future changes in precipitation based on RCMs forced by GCMs for mainland Portugal, using EURO-CORDEX models. The EURO-CORDEX is the European branch of the CORDEX initiative and produces, on a regular basis, ensemble climate simulations based on multiple dynamical and empirical-statistical downscaling models forced by multiple global climate models from the different CMIP simulations (Giorgi et al. 2009). A large fraction of regional climate change assessment studies uses the outputs from the EURO-CORDEX models to produce high resolution scenarios for Europe (Soares et al. 2017; Prein et al. 2015; Kotlarski et al. 2014). Soares et al. (2017) analyzed different EURO-CORDEX models, and constructed multimodel ensembles concluding that performed better than the individual models (by comparing model results and observations using different error metrics). Also, the authors found that RCP 4.5 and RCP 8.5 share the same climate change signal, though different magnitudes, and that Portugal mainland is highly vulnerable to climate change. It was also shown by Soares et al. (2017) that the normalized precipitation PDF changes show a considerable reduction in the frequency of daily rainfall below ~20 mm, which is accompanied by an increase in events with daily precipitation above this threshold. In fact, for Portugal, the contribution for the total precipitation shifts importantly from light/moderate-intense to strong precipitation.

Also, Santos et al. (2019) studied recent and future changes in precipitation extremes over Portugal, regarding the trends in selected precipitation indices for the periods of 1950–2003 and 2046–2065, at a seasonal and annual scale. The authors considered the possible climate change effects of the RCP 8.5 scenario and showed that more extreme precipitation tends to occur in autumn than in winter and that the contribution of extreme precipitation to total precipitation tends to increase. While it is expected an increase in extreme precipitation, the annual precipitation over northern and central Portugal shows a decreasing trend. In general, Santos et al. (2019) showed that the northern region will be more susceptible to extreme precipitation events while the southern region will be more susceptible to long drought events.

Recent works, also, analyzed future rainfall conditions based on climate scenarios to evaluate landslide susceptibility. Hurlimann et al. (2021) used EURO-CORDEX climate models and the IDRISI TerrSet software to compute landslides susceptibility maps. The authors found an increase in daily rainfall between 14 and 26%, assuming a return period of 100 years, thus leading to a decrease of the stability condition in the study area. This study showed differences between different land cover types, being that the forest area will significantly increase. So, the stability condition improves, since the root strength is higher in forest, hence this positive effect is larger than the negative influence of rainfall changes. Lin et al. (2020) evaluated the impact of climate change by using GCMs to determine the cumulative event rainfall duration threshold in areas highly susceptible to landslides in China. The authors showed an increase in landslide occurrence under all GCMs (between 19.9 and 33.2%) in the late twenty-first century, considering the RCP 4.5 and RCP 8.5 scenarios, respectively. This study showed that the assessment of the effect of climate change on landslides is not straightforward based on only the precipitation-related proxy.

This work aims to evaluate the EURO-CORDEX models' ability to reproduce extreme precipitation, regarding the definition of an intense rainfall event that may induce a landslide event. Thereby, we aim to achieve three main objectives: (1) to use the DISASTER database in order to analyze the spatial and temporal frequency of the landslide activity under the different regions to be studied; (2) to compute the highest percentiles' values and RTTs regarding observed and simulated precipitation; and (3) to evaluate future evaluation of the simulated highest percentiles' values and the RTTs' percentiles, following two climate change scenarios: RCP 4.5 and RCP 8.5.

Study area

Portugal is located in the southwestern part of Europe, being characterized for its Mediterranean climate south of the Tagus River and a more Atlantic wetter regime in the northern half (Cardoso et al. 2013). The country is characterized by an irregular rainfall regime and strong interannual and intra-annual variability (Kutieli and Trigo 2014). This strong interannual variability translates into wet years followed by several dry years (Vaz et al. 2018). As for the intra-annual variability, 75% of the annual rainfall is registered between October and March, whereas September, April, May, and June correspond to transition months with few rainfall events, though it can vary yearly depending on the interannual variability (Vaz et al. 2018). The rainfall regime varies spatially, being the northern region wetter than the southern (Soares et al. 2012a, b, c),

which is associated to several factors, such as the latitudinal location (between the subtropical ridge and the sub-polar depression belt), the proximity to the Atlantic Ocean, the irregular distribution of orography, and the influence of the most important teleconnection patterns of the Euro-Atlantic region (NAO and EA) (Trigo et al. 2008; Santos et al. 2015, 2016, 2017; Melo-Gonçalves et al. 2016). The extended winter mean accumulated precipitation for the 1971–2000 period and the intra-annual variability of the precipitation for the two locations for the period 1971–2000 are shown in supplementary material Fig. S1.

To simplify the assessment of the extreme rainfall and landslide activity, rather than evaluate all Portuguese domain, two study areas were chosen because they are well known to be representative of the most susceptible regions for the occurrence of landslides in mainland Portugal, belonging to very different geomorphological settings (Zêzere et al. 2014; Pereira et al. 2018): *Sobral de Monte Agraço* (39°N, 9.2°W) and *Santa Marta de Penaguião* (41.2°N, 7.8°W). The first belongs to the Grande da Pipa River (GPR) basin which is located in the north of Lisbon region and is included on the Portuguese West Meso-Cenozoic sedimentary basin (Fig. 1). In the GPR basin, superficial and deep-seated slow moving landslides of the slide type are more frequent and controlled primarily by lithology (mainly sedimentary rocks from the Kimmeridgian to the lower Tithonian, Upper Jurassic), geological structure, and hydrogeological conditions, being shallow soil slips more concentrated in steeper slopes ($> 15^\circ$), and deep-seated slides more frequent in the presence of more gentle slopes (5° – 15°) (Ferreira and Zêzere 1997; Zêzere et al. 2014, 2015; Oliveira et al. 2015). The second study area is situated in the Douro Valley (DV) region, Northern Portugal, and is part of the Iberian Massif, mostly composed by metamorphic rocks (Cambrian), quartzites (Ordovician–Silurian), and granites (Pereira et al. 2017). In the DV region, shallow slides and debris flows are dominant. Slope movements affecting slope deposits and the underlying weathered bedrock are frequent in metasediments (e.g., schist and slate) whereas the weathering mantles in granitic substratum are particularly prone areas to debris flows (Zêzere et al. 2015). These landslides tend to reach higher speeds and a greater destructive potential (Zêzere et al. 2014). For the sake of brevity throughout this work, the sites' coordinates of *Sobral de Monte Agraço* and *Santa Marta de Penaguião* will be called SMA and SMP, respectively (Fig. 1).

Data

Landslide events database

In this work, the comprehensive and long-term DISASTER database, developed by Zêzere et al. (2014) and later updated by Pereira et al. (2018), was used to assess the landslide activity over Portugal mainland. Spanning from 1865 to 2015, this database only considers hydro-geomorphological disasters (landslides and floods) that caused human consequences in Portugal mainland. The information about the type of disaster cases was collected not only through daily and weekly newspapers published at the national level but also a few regional printed media, to achieve an extensive spatial coverage (Pereira et al. 2018; Zêzere et al. 2014). A DISASTER case is — in this context — a unique hydro-geomorphologic occurrence, which fulfills the database criteria, and is related to a unique space location and a specific period of time (Zêzere et al. 2014). These are

later “grouped into a set of discrete disaster events that share the same trigger mechanism and a specific magnitude in time” (Pereira et al. 2018). The authors identified 130 disaster events between 1865 and 2015, from which 67 are related with damaging landslide events (Pereira et al. 2018).

Precipitation data: “IB02”

For the observational daily precipitation data, the Iberia02 (IB02) dataset was used. IB02 is a high-density daily precipitation gridded dataset that covers the Portuguese and Spanish domains between 1950 and 2008, at a 0.2° spatial resolution (Ramos et al. 2014). According to Ramos et al. (2014), this dataset was developed by Portuguese and Spanish meteorological offices, obtained through the merge of the daily precipitation available for mainland Portugal (PT02, Belo-Pereira et al. 2011) with the daily precipitation available for Spain (SPAIN02, Herrera et al. 2012). This dataset includes information from more than eight hundred stations over Portugal and two thousand over Spain (Ramos et al. 2014; Trigo et al. 2016). Moreover, this dense network of rain gauges has been quality-controlled and homogenized (Ramos et al. 2014, 2017; Trigo et al. 2016) allowing regional assessments of extreme precipitation over relatively small areas (Trigo et al. 2016).

EURO-CORDEX simulations

The World Climate Research Programme (WCRP), in 2009, created the CORDEX program with the aim of generating regional climate change simulations for all global land zones within the timeline framework of the Fifth Assessment Report (AR5) and beyond (GERICS 2020). The CORDEX applied the same rationale to a common European domain (EURO-CORDEX), thus producing an ensemble of climate simulations based on the forcing of RCMs by GCMs (Jacob et al. 2014, 2020). The daily precipitation dataset used by EURO-CORDEX was retrieved from the Earth System Grid Federation portal (Soares et al. 2017). These simulations were performed at two spatial resolutions: 0.11° (~ 12.5 km) and 0.44° (~ 50 km) for a historical and future climate periods, and consisted of several RCMs forced by different GCMs and RCPs scenarios (Soares et al. 2017).

In this work, it was considered the 0.11° spatial resolution since the purpose was to analyze hydro-geomorphological disasters at the finest resolution available allowing us to reduce the error regarding the nearest point from each studied location from the IB02 dataset. The use of a regular gridded dataset (IB02) is related to the fact that models' precipitation output corresponds to an aerial average over each grid box, and to be comparable with observations, we should also consider a precipitation gridded value and not a point-local rainfall amount.

This analysis was performed for a historical period between 1971 and 2000 and for a late twenty-first century period, between 2071 and 2100. The climate change scenarios considered include the two Representative Concentration Pathways: RCP 4.5 and RCP 8.5. More information about the RCPs can be found in van Vuuren et al. (2011). The portfolio of EURO-CORDEX simulations is continuously updated, hence more RCM-GCM combinations are available. However, the number of simulations including the RCP 4.5 scenario was

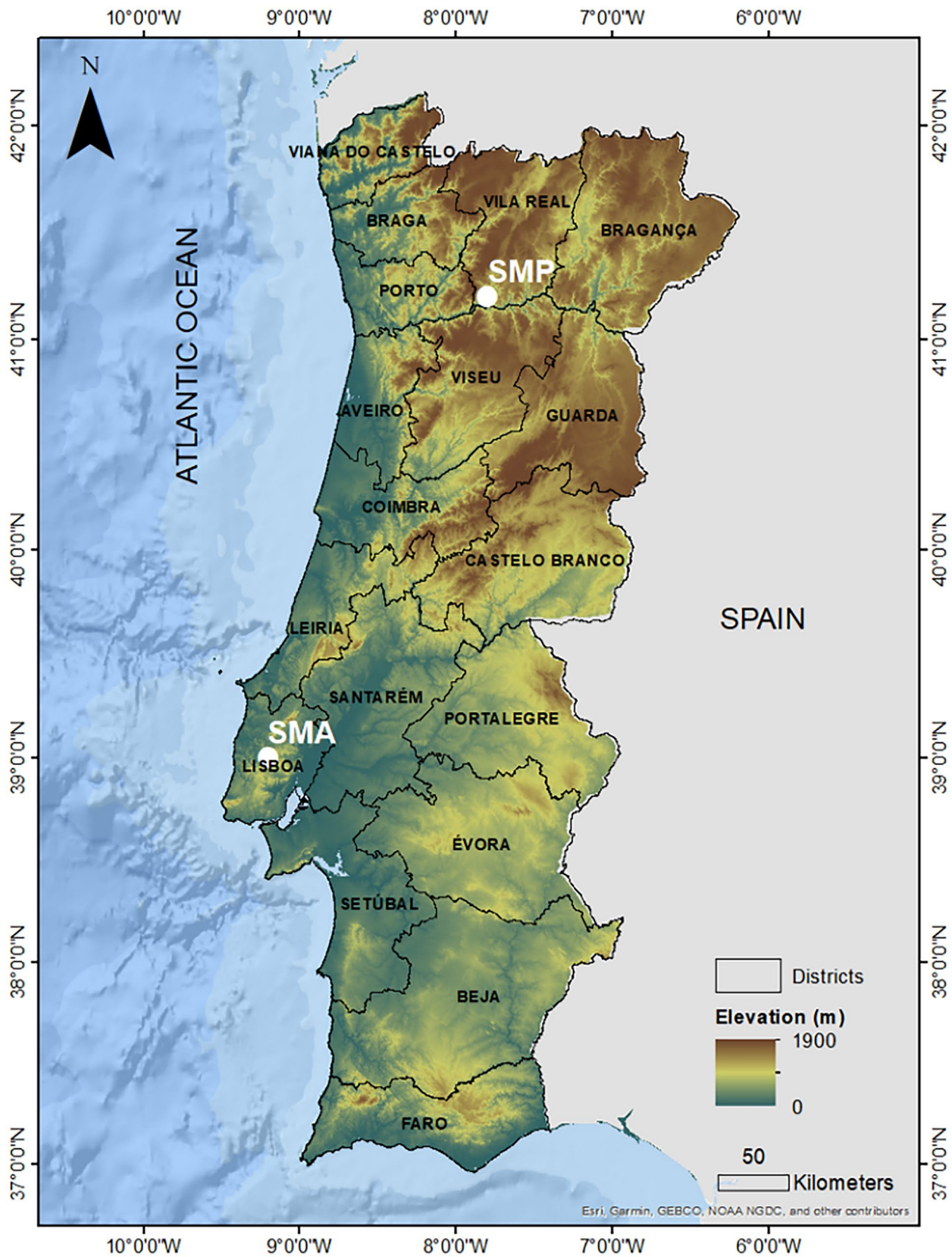


Fig. 1 Map of Portugal mainland with the two sites considered: Sobral de Monte Agraço (SMA) and Santa Marta de Penaguião (SMP)

lesser than for the historical and RCP 8.5 simulations. Therefore, we only considered the combinations common to all, which was a total of 15 combinations of EURO-CORDEX RCM-GCM models' runs (Table S1). The analysis of these EURO-CORDEX models is similar to the one by Soares et al. (2017), although a few extra models were used since the portfolio of EURO-CORDEX simulations is updated continuously. Briefly, this work considered the combination of 6 different GCMs and 7 RCMs. More details about parametrization used in each RCM are depicted in Kotlarski et al. (2014) and Katragkou et al. (2015).

The precipitation assessment in the sites, SMA and SMP, relied on the observational precipitation data from Iberia02 (IB02), and on the precipitation data from EURO-CORDEX models' runs at the nearest point from each location.

Methods

Landslide events: DISASTER database analysis

In this work, the period of interest spans between 1971 and 2000 and the 67 hydro-geomorphological events that have had damaging landslides in the DISASTER database. First, we evaluated the seasonal cycle of the monthly damaging landslide frequency. This approach aimed to compare the monthly landslide frequency at the historical period with the landslide frequency at the database timeline, and to evaluate the months with more damaging landslide activity.

Then, we calculated the RTTs, with the database information and with the IB02 dataset. This approach followed the methodology implemented by Zêzere et al. (2005, 2015). The methodology to define the critical rainfall combination for each landslide event relied on empirical methods of linear regression between the amount of precipitation and the consecutive days of accumulated antecedent precipitation that triggers the slope instability in the area (Zêzere et al. 2005, 2015). Studies developed for the same region, including Zêzere (2000), Zêzere and Rodrigues (2002), and Trigo et al. (2005), showed that critical rainfall conditions that can trigger slope movements are not equal for different landslide types. According to Zêzere et al. (2005), shallow landslides commonly occur within 1 to 15 days of intense rainfall, whereas deep-seated landslides tend to take place when prolonged precipitation falls for consecutive weeks, which typical range between 30 and 90 days. In fact, Zêzere et al. (2005) resorted to previous investigation, field work, interviews, and rainfall analysis, in order to reconstruct the past landslide activity and the absolute cumulative rainfall from 1 to 90 days. In this assessment of RTTs, the authors had to consider

the rainfall events that triggered landslides in a specific period and the rainfall events that did not trigger landslides in the same period (Vaz et al. 2018). Thus, two distinct rainfall thresholds were achieved: (1) *the lower-limit threshold, "which is the limit below which landslides have not been recorded,"* and (2) *the upper-limit threshold, "which is the limit above which landslides have always been recorded"* (Glade et al. 2000). The range between the lower-limit and the upper-limit thresholds corresponds to the zone where landslide events may occur, with different probabilities of occurrence, since the uncertainty increases with the gap between the two thresholds (Vaz et al. 2018).

For this work, and using the methodology described above, four thresholds were determined for each one of the locations (SMA and SMP), considering different values of consecutive days of accumulated precipitation, namely, 1D (1 day), 10D (10 days), 30D (30 days), and 60D (60 days) (Table 1).

Santa Marta de Penaguião (SMP) is a municipality in the northern region of Portugal for which a detailed geomorphological-based landslide inventory, with almost 900 landslide records, is available. The inventory includes 71 damaging landslides that were responsible for three fatalities, one homeless person, two destroyed buildings, and 71 road disruptions (Pereira et al. 2014). Regarding the GPR basin, located within the SMA site, is recognized as a major landslide prone area in the northern region of Lisbon (Garcia and Oliveira 2020), presenting structural, geomorphological, and climatic conditions which favor a very active slope evolution, where landslides take an important role.

These RTTs were obtained for the hydrological winter half-year, that is, from October to March. Also, since the aim was to analyze all possible landslide events that may occur, it used the lower-limit threshold.

High ranking precipitation percentiles

By definition, in a normal distribution, the extreme values correspond to the higher percentiles that correspond to the most improbable events. Therefore, in this work, the percentiles 75th, 95th, 97.5th, 99th, and 99.9th were computed for the four different precipitation accumulated time series over different time periods regarding the occurrence (or not) of dry days in order to study the accumulated precipitation over different time lags. Therefore, we did a running-window for the accumulated periods, so for each day, we have computed the accumulated antecedent rainfall for the durations of 1, 10, 30, and 60 days. For example, the accumulated

Table 1 IB02 rainfall triggering thresholds for the two sites considered and the four chosen timescales. The rainfall triggering thresholds chosen are highlighted

	SMA			SMP		
	Lower limit (mm)	Linear regression (mm)	Upper limit (mm)	Lower limit (mm)	Linear regression (mm)	Upper limit (mm)
1D	38.4	122.1	173.8	65.4	135.3	352.2
10D	80.0	177.9	234.5	146.7	226.4	455.9
30D	172.5	301.8	369.5	327.2	428.9	686.2
60D	311.3	487.8	572.0	598.1	732.7	1031.6

of 10D represents the precipitation falling between day 1 till day 10 (PREC_accumulated_10_day1), while PREC_accumulated_day2 corresponds to precipitation falling between day 2 and day 11 and so on. This is in line with similar methodology applied successfully in previous studies that analyzed regional rainfall thresholds for landslide occurrence in Portugal (e.g., Zêzere et al. 2005; Vaz et al. 2018).

Another purpose of this study relied on the assessment of rainfall-induced landslide events, so the RTTs' percentiles were, also, considered in order to evaluate the likelihood of these events and the possible projected changes in the future precipitation series. This assessment was restricted to the hydrological winter half-year (October to March), since it comprehends the majority of annual rainfall over Portugal mainland.

In addition to the computation of the daily precipitation (1D), the remaining three different precipitation series were computed by accumulating the daily precipitation in 10, 30, and 60 consecutive days for each one of the sites (*SMA* and *SMP*). The daily precipitation values and the consecutive days of accumulated precipitation series considered had to exceed 1 mm. This method was applied to the IBO2 precipitation dataset and to the EURO-CORDEX models' runs. In this work, a multimodel ensemble was adopted. The most common methodology for multimodel ensemble building is simple or weighted average. The latter considers the individual models' performance. However, when evaluating extreme values, such averages cannot be made since it led to a strong smoothing of the data (Weigel et al. 2010). The multimodel ensemble, adopted in this work, is based on pooling together all the model's precipitation data, at the different accumulation time intervals, i.e., to build a synthetic precipitation dataset including all the models for which the percentiles are calculated. With such an approach, we avoid the undesirable smoothing of averaging techniques for extreme values allowing a realistic statistic of different samplings considering all temporal and spatial reality (Soares et al. 2012a, b). Since we are comparing statistics and not the time series itself, this approach can be made.

First, the models' ability to simulate the high precipitation values was evaluated. To do so, a comparison between the highest percentiles' values from IBO2 and EURO-CORDEX models' runs (including the multimodel ensemble) was made. In this comparison, we considered a historical period (between 1971 and 2000) and evaluated each site and timescale. In this assessment, the RTTs' percentile was computed from the IBO2 precipitation dataset. Then, to evaluate the possible future changes, we used concentration scenarios, namely, RCP 4.5 and RCP 8.5. In this case, the highest percentiles' values were obtained only through the EURO-CORDEX models' runs (including the multimodel ensemble), and we compared the simulations for the historical period with the simulations for end of the century (2071–2100), considering both RCP scenarios. Also, in this assessment, we evaluated each site and timescale. Given the amount of information provided, we further analyze the most representative percentiles, namely, the 75th, 95th, and 99th in terms of future climate change projections.

In addition, we acknowledge that the use of current bias correction methods is widely debatable in the scientific community for extreme values (e.g., Maraun et al. 2017), and therefore, we opted to not introduce bias correction. The assumption that biases will hold in a future climate is critical and very implausible for precipitation extremes.

Finally, we wanted to evaluate the changes in the RTTs' percentiles, that is, if the percentile associated to the amount of rainfall that in the past led to a landslide occurrence, in the future will be associated to a more or less likely event, lower or higher percentile, respectively. Thus, first we calculated the RTTs' percentiles from the historical EURO-CORDEX simulations, for each site and timescales. Then, we calculated in the future (2071–2100) EURO-CORDEX models' runs (including the multimodel ensemble), the amount of accumulated precipitation associated to those percentiles obtained previously. This assessment was elaborated considering both RCP 4.5 and RCP 8.5, and for each site and timescale. To evaluate the possible changes in the percentiles associated to the RTT, a comparison between the RTTs and the EURO-CORDEX simulations, for the future period, of the amount of precipitation associated to RTTs' percentiles was made, for each site and timescale. Therefore, through this analysis, it is possible to ponder if rainfall-induced landslides will become more, or less, frequent, at the end of the century, under different climate change scenarios. To evaluate more precisely the projected future changes in the extreme values, a simple relative difference was made between the amount of precipitation of the multimodel ensemble, projected for the end of the century, and the amount of precipitation correspondent to the RTTs, in order to quantify the projected increases or decreases.

Results and discussion

Landslide events: DISASTER database analysis

The landslide events frequency was evaluated for the historical period considered in this work (Fig. 2). The main goal in this landslide frequency analysis was to compare the historical period with the database timeline, in order to evaluate if this historical period could be a representative period of landslide activity. The period between 2001 and 2015 was also depicted in order to evaluate the increasing frequency of these events in recent years.

For the historical period, Fig. 2 shows that the months with more landslides were observed between November and February, with a peak in December and January. These months correspond to the late autumn and winter seasons in Portugal, which are associated to

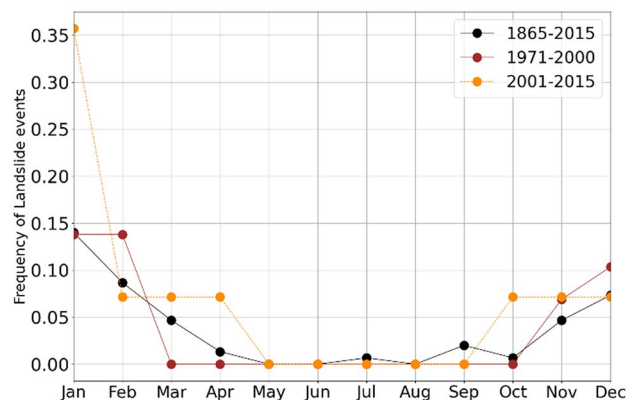


Fig. 2 Frequency of landslide events per month for the DISASTER database timeline (1865–2015), for the historical period (1971–2000), and for the most recent period within the DISASTER database timeline (2001–2015)

the highest values of rainfall (Trigo and DaCamara 2000). The months spanning between March and October did not have landslide events between 1971 and 2000, mostly because these months correspond to the spring and summer drier seasons.

In Fig. 2, we can observe two sub-periods within the much longer DISASTER database timeline. The important point to stress is that during the 30-year period between 1971 and 2000, the seasonal cycle of monthly landslide frequency appears to be relatively similar to the 150-year period, and so the 30-year shorter period can be considered to hold some representativeness of the landslides annual cycle. Nevertheless, despite the resemblance, it is interesting to stress that the frequency of landslide events in the 30 years was slightly higher than the corresponding late autumn and winter seasons frequency in the DISASTER database (Fig. 2). From this comparison, we can evaluate that the months of February, November, and December showed higher frequency in the 30-year period, and the months of January, March, April, July, September, and October showed larger frequency in the 150-year period. In addition, it is also possible to observe that the period between 2001 and 2015 exceeds the 30-year and 150-year landslide frequency in January, March, April, and October, which reveals that the frequency of landslide activity is in fact increasing in these months, in recent years. From the 67 landslide events, recorded in the DISASTER database timeline, most occurred between October and March. Therefore, this analysis converges with the statements established before that these months would be the period of interest for the precipitation assessment.

Extreme precipitation

We used two complementary approaches to evaluate future changes in the occurrence of extreme values, namely, through the highest percentiles in the precipitation series and through the RTTs' percentiles. The highest percentiles considered were the 75th, 95th, 97.5th, 99th, and 99.9th, and the precipitation series used were the daily (1D), ten (10D), thirty (30D), and sixty (60D) consecutive days of antecedent accumulated precipitation, from both IBO2 dataset and EURO-CORDEX models' runs for historical and future periods, for the two locations considered. In this first approach, two comparisons were made: (1) the models' performance simulating extreme values — *Historical IBO2 vs Historical EURO-CORDEX models' simulations* (Fig. 3); and (2) the projected changes in the most representative percentiles — *Historical EURO-CORDEX models' simulations vs Future EURO-CORDEX models' simulations* (Fig. 4). In the second approach, the RTTs' percentiles were obtained from the EURO-CORDEX simulations for the historical period and then, the amount of precipitation associated to those percentiles at the simulated precipitation series for the end of the century, from EURO-CORDEX, were calculated. In this approach, one comparison was made between *RTTs vs the amount of precipitation associated to RTTs' percentiles for the end of the century* (Figs. 5 and 6). The future models' simulations used in the two approaches considered both scenarios RCP 4.5 and RCP 8.5.

Figure 3 shows which models have a better agreement with the observed data (IBO2) for *SMA* and *SMP*. In all figures, including their subplots, it is perceptible that the higher the percentile, the larger the spread between models. That is, the 75th percentile shows better agreement, between the models and IBO2, whereas the 99.9th

percentile displays a larger spread, although some models reveal a good agreement. Each individual model does not have the same behavior in all percentiles, that is, a model can represent better the extreme precipitation at the percentiles 95th and 99th, whereas in the 99.9th, the agreement is worst. The same observation is applicable to different consecutive days of accumulated precipitation, which means that a model can have a very good agreement in the 30 consecutive days of accumulated precipitation and a poor match in the 10 consecutive days. These differences also apply when considering the two locations, that is, a model that shows a good agreement in the extreme precipitation at *SMA* can present a worse agreement at contiguous *SMP*. Another observation shared by these two sites is that as the consecutive days of accumulated precipitation increase, the spread between models becomes larger. Although the aim of this analysis is a more general discussion of all models and the multimodel ensemble, rather than an evaluation of individual models, through this approach, it is possible to evaluate each model individually and its contribution for a weighted multimodel ensemble for extreme precipitation, regarding the EURO-CORDEX models.

The two sites considered (*SMP* and *SMA*) are located in distinct geomorphological contexts and present also different rainfall variability which translates in a larger spread between models in all timescales and percentiles. In these two sites, most models overestimate the extreme precipitation associated with the percentiles 95th, 97.5th, 99th, and 99.9th at the daily precipitation (Fig. 3a, c), and underestimate the extreme precipitation associated with the percentiles 95th, 97.5th, 99th, and 99.9th at the 30D timescale (Fig. 3b, d). In Fig. 3, only two timescales are presented (1D and 30D) for each site, since the 10D and 60D have a similar behavior with the 30D. Nevertheless, these two timescales can be found in the supplementary material S2.

Overall, there is no single model that reveals results at all timescales for both sites, i.e., all of them reveal caveats. Therefore, we have employed the pooling together approach that artificially extends the time series stitching together the output from all models (Soares et al. 2012a, b). We chose, for this pooling together methodology, all models since there is no model that represents well the extreme precipitation simultaneously at both sites and timescales, as mentioned before.

According to Table 1, the RTT for the daily precipitation lower-limit threshold based on IBO2 dataset over *SMA* and *SMP* is 38.4 mm and 65.4 mm, respectively, corresponding in observations to the 99.12th and 99.78th percentiles. For the accumulated precipitation over 30 consecutive days, the RTT at *SMA* and *SMP* is 172.5 mm and 327.2 mm, which corresponds, in the observed data, to the 84.79th and 93.45th percentile. For these sites, as the consecutive days of antecedent accumulated precipitation increase, the RTTs' percentiles decrease. In *SMA*, the threshold's percentile becomes closer to the third quantile, whereas in *SMP*, it is closer to the 95th percentile. This shows that is less likely to equal or exceed the RTT of 30 consecutive days of accumulated precipitation in *SMP* than in *SMA*. By observing the percentiles closest to the RTTs' percentiles, at the daily timescale, we can perceive that for *SMA* and *SMP*, the models show a spread of circa 30 mm and 60 mm, respectively. As for the 30D timescale, the spread becomes larger: 120 mm and 280 mm. As mentioned above, *SMP* shows the largest spread between models when compared to *SMA*. These differences

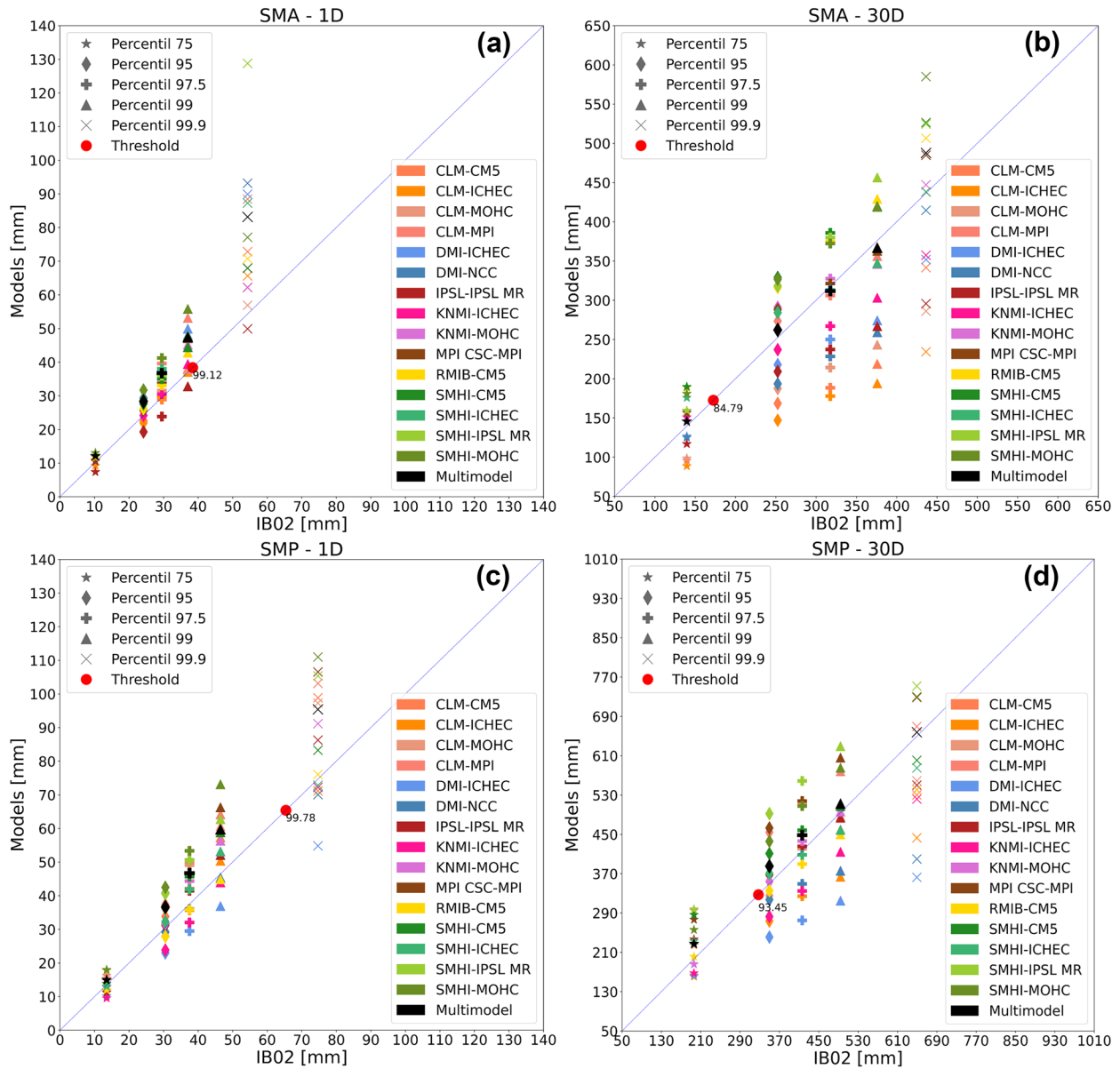


Fig. 3 Precipitation of each percentile, for every EURO-CORDEX combination of RCM-GCM and IB02 for SMA (a and b), and SMP (c and d), between 1971 and 2000, considering the daily and thirty consecu-

tive days of antecedent accumulated precipitation. The RTT is also marked (red dot), as well as its percentile

between the two sites stress the difficulty to obtain very good simulations, capable of reproducing the higher percentiles of the precipitation distributions.

Comparing the performance of each model and multimodel ensemble to estimate the highest percentiles' values, we observed that the multimodel ensemble was the model that simultaneously in all timescales and in each site presented relative differences within -20% and 20% (Figs. S5 and S6 and Table S2 in the supplementary material). The same does not apply for any model, since their performance changes a lot according to timescale and site. Therefore, the outcome of the multimodel ensemble for SMA and SMP showed an overall good agreement with the observed data, in

all four timescales considered. Thus, in this study, the multimodel ensemble may be considered one of the best representing models for extreme precipitation in the considered geographical sites.

The assessment of the projected future changes in precipitation extremes, following two concentration scenarios, RCP 4.5 and RCP 8.5, can be observed in Fig. 4, considering the models' simulations over SMA, at 1D and 30D, and over SMP, at 30D. This analysis is focused in the most representative percentiles, namely, 75th, 95th, and 99th. The evaluation of the projected future changes in the extreme values over SMA, at 10D and 60D, and over SMP, at 1D, 10D, and 60D, can be found in the supplementary material Figs. S3 and S4. For all sites, at the daily timescale, most

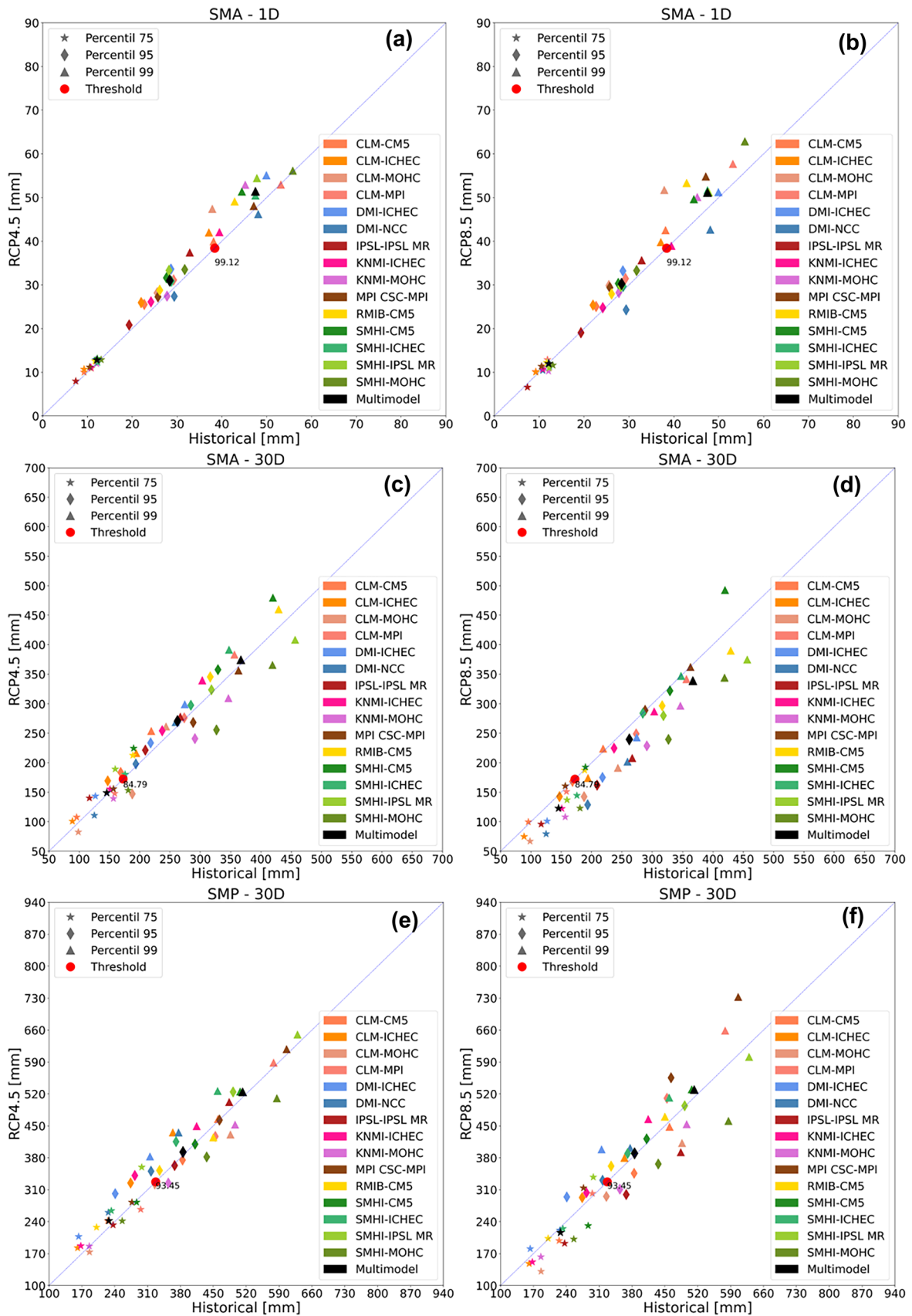


Fig. 4 Extreme precipitation associated to the percentiles 75, 95, and 99, over SMA at 1D (a and b) and 30D (c and d), and SMP at 30D (e and f). Both RCP 4.5 (a, c, and e) and RCP 8.5 (b, d, and f) considered. The RTT is also marked (red dot), as well as its percentile

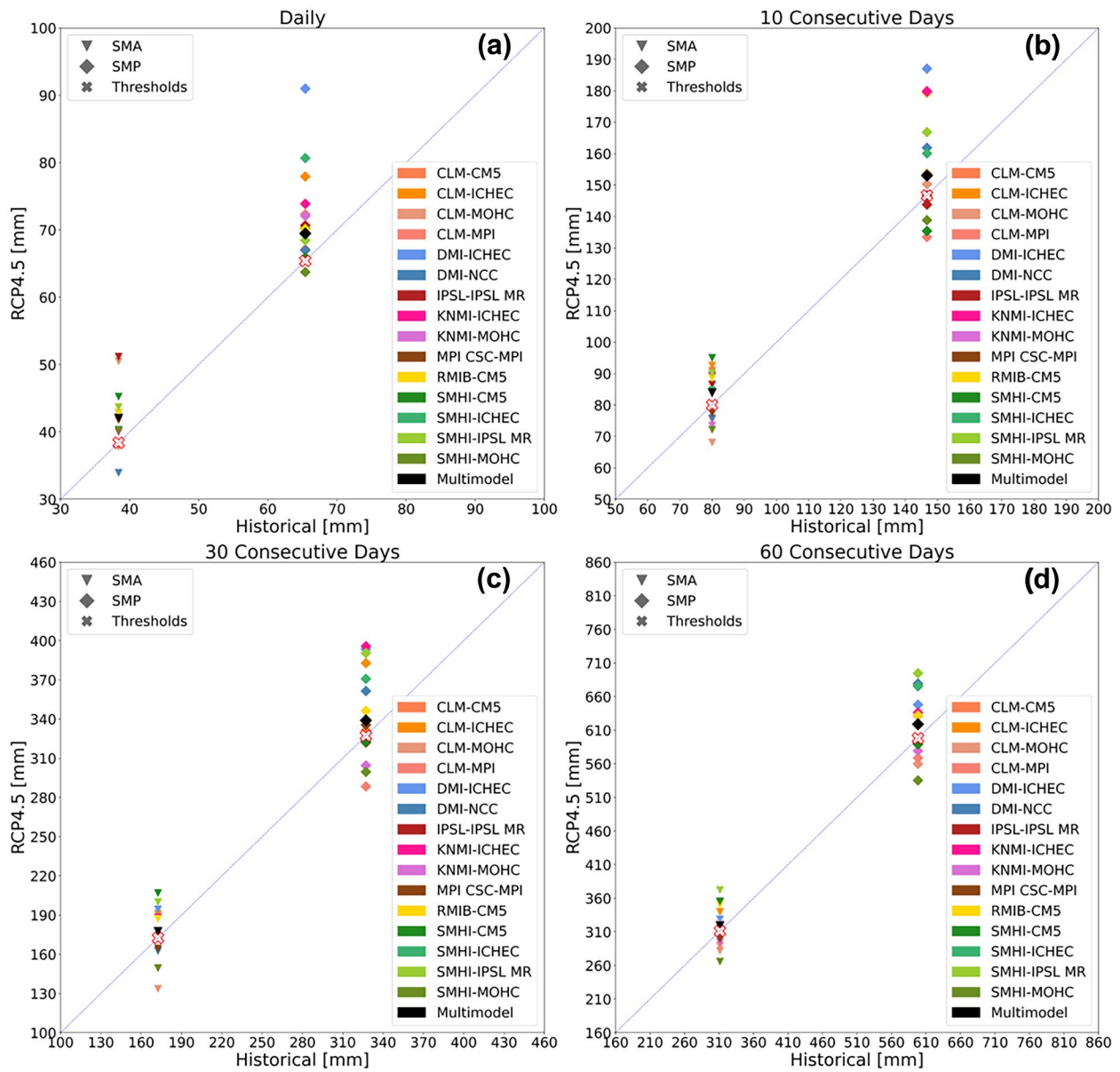


Fig. 5 Future changes, following RCP 4.5 scenario, in the precipitation associated to the RTTs' percentile, for the end of the century, relative to the RTT at the historical period. **a** 1D, **b** 10D, **c** 30D, and

d 60D, for both locations. The sites' threshold of the correspondent timescale is marked by an x

models projected an increase in the precipitation associated to the percentiles considered, when following both RCP scenarios. For the timescales of 10D, 30D, and 60D, the projected changes are dissimilar. In these timescales, most models projected an increase in the extreme precipitation when following the RCP 4.5, and when following the RCP 8.5, most models projected a decrease. However, in *SMP*, the number of models that projected a decrease, in the longer timescales, appeared to be almost balanced by the number of models that projected an increase (Fig. 4), when following the RCP 8.5 scenario. Since, in Fig. 4, we cannot perceive the quantitative value of these increases and decreases, for each site, is presented in the supplementary material, which shows in

fraction the projected increases and decreases (Figs. S7, S8, S9 and S10 in the supplementary material).

As previously described, the methodology for assessing extreme precipitation relied on two approaches. The second approach is based on the evaluation of the future change in the amount of precipitation correspondent to the RTTs' percentiles obtained from the EURO-CORDEX simulations (Figs. 5 and 6). This was evaluated also considering each timescale, for each site and RCP scenario. By observing Fig. 5, we can notice that most models, following the RCP 4.5 scenario, project an increase in the amount of precipitation associated to the RTTs' percentile for all timescales, for the end of the century. Likewise, at the daily timescale, when following the RCP

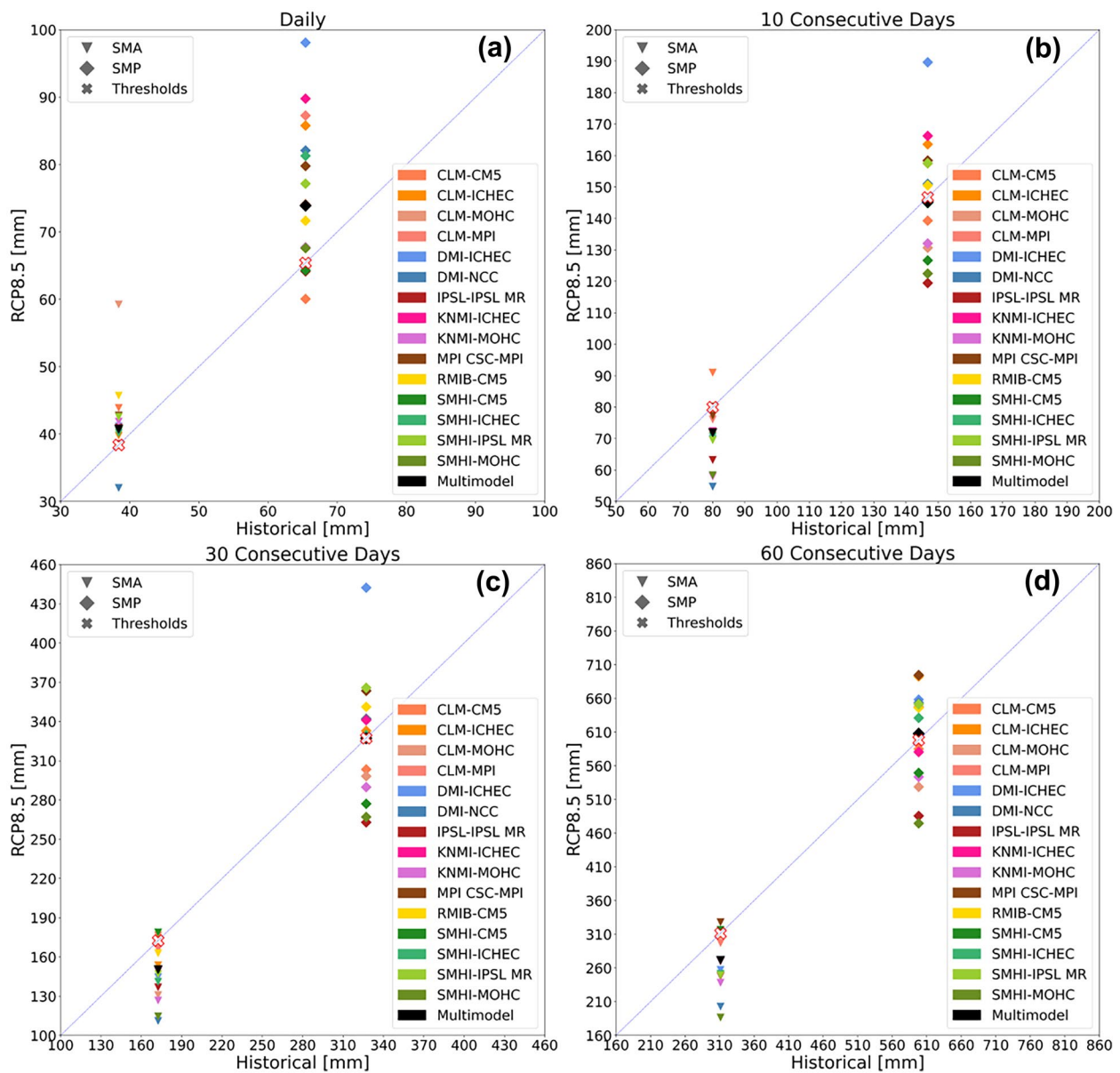


Fig. 6 As in Fig. 5 but following RCP 8.5 scenario. The sites' threshold of the correspondent timescale is marked by an x

8.5 scenario, most models project an increase over the two sites. As for the 10D, 30D, and 60D timescales, when following the RCP 8.5 scenario, the observations vary between locations, with most models at SMA projecting a decrease of the precipitation associated to the RTTs' percentile, whereas at SMP, the number of models that project an increase is almost balanced by the models that project a decrease. In the previous assessment, as well as in this evaluation, SMP is the location with the largest spread between models in all timescales, and for both RCP scenarios.

According to the models' performance to simulate extreme values in the precipitation series, the multimodel ensemble had a good agreement, and stood out as one of the best performing models. Thus, observing in Figs. 5 and 6 the multimodel ensemble signal, we can understand better the projected future changes of extreme

precipitation under climate change scenarios. Likewise, the majority of models, the multimodel ensemble projects an increase, at all timescales when following the RCP 4.5 and at daily timescale when following the RCP 8.5, although with different magnitudes depending on location and timescale. At the 10D, 30D, and 60D, the multimodel ensemble, following the RCP 8.5, points towards a decrease in the precipitation associated to the RTTs' percentile, over SMA. Hence, in general, the precipitation associated to the RTTs' percentile tends to become more likely for a future that follows RCP 4.5 scenario, and less likely for the RCP 8.5 scenario.

For a better evaluation of the magnitude and signal of the projected changes in the precipitation associated to the RTTs' percentile simulated by the multimodel ensemble, we quantified this change through a simple method of relative differences between the

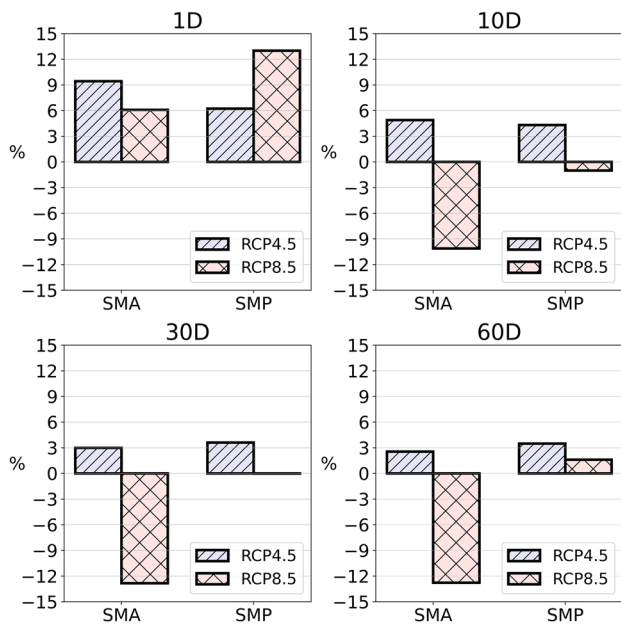


Fig. 7 Relative differences (in percentage (%)) between the projected future extreme precipitation associated with the RTTs' percentile, and the amount of precipitation correspondent to the RTT, for the multimodel ensemble, at 1D, 10D, 30D, and 60D, for the two locations and both RCP 4.5 and RCP 8.5 scenarios

amount of precipitation correspondent to the RTTs and the amount of precipitation projected by the multimodel ensemble (Fig. 7). Observing Fig. 7, it is possible to synthesize the previous statements. That is, at 1D timescale, it is projected an increase, following both RCP scenarios, with magnitudes varying between circa 6 and 10%. At 10D, 30D, and 60D, when following the RCP 4.5 scenario, it is projected an increase, over both sites, of circa 5%. While, when following the RCP 8.5 scenario, at those timescales, it is projected a decrease, over SMA, with circa 10–13%. Over SMP, when following RCP 8.5 scenario, it is projected smaller changes between –3 and 3%. According to this analysis and Figs. 5 and 7 (RCP 4.5), we can understand that the percentile that before corresponded to the RTT, that might induce a landslide event, at the end of the century, it is expected to be associated to more precipitation; therefore, the RTT becomes an event more likely. According to Figs. 6 and 7 (RCP 8.5), at 10D, 30D, and 60D, over SMA, the percentile that before corresponded to the RTT, at the end of the century, it is expected to be associated to less precipitation; therefore, the RTT becomes an event less likely, whereas, following the same scenario (RCP 8.5), the RTT of 1D will become an event more likely for both sites.

Conclusions

Extreme weather is becoming more frequent, and some climate change projections highlight that southern Europe will be the most susceptible European region to these extreme events. According to several studies that focused on the future changes in the precipitation extremes over Portugal (e.g., Soares et al. (2017) and Santos et al. (2019)), it is expected an increase in the frequency and magnitude of extreme precipitation, due to climate change. Hence, geomorphological events that are rainfall-induced, like landslides, will also likely become more frequent (IPCC 2014). This work is focused

on rainfall-induced landslide events, through the assessment of the impact of extreme precipitation in future landslide activity, following two distinct concentration scenarios and using 15 EURO-CORDEX models, over two Portuguese locations: SMA and SMP.

For Portugal, the relationship between the occurrence of rainfall-induced disaster events and the exposed and vulnerable population has been established, to manage disaster risk, within the context of the comprehensive and long-term DISASTER database (Pereira et al. 2018; Zêzere et al. 2014). In what concerns the correlation between landslide activity and extreme rainfall, Zêzere et al. (2005, 2015) and Vaz et al. (2018) developed RTTs based on empirical methods of linear regression, to identify the amount and duration of precipitation necessary to induce a landslide event. Here, we adapted their approach to compute the RTTs.

Santos et al. (2019) and Soares et al. (2017) were used as a reference framework for the extreme precipitation assessment. Santos et al. (2019) found increasing trends in precipitation extremes and conclude that the Portuguese northern region is more susceptible to extreme precipitation while the southern region is particularly susceptible to long droughts. Soares et al. (2017) also indicated an increase of extreme precipitation under climate change scenarios that in some areas of Portugal mainland may reach values above 50%. A recent study (Vaz 2021) detected an increment in the precipitation intensity between 1980 and 2008 corresponding to shorter return periods of extreme precipitation events, increasingly associated to the occurrence of landslides by comparison with the previous period (1950–1980). Moreover, some recent evidence is pointing out to the likelihood that landslides in mainland Portugal are occurring earlier in the climatological year and are triggered by shorter rainfall events associated to higher intensities (Vaz 2021). Similar trends were found by Gariano et al. (2021) for the Umbria region (Italy).

We applied a sequential number of methodological steps to adjust observed and modeled extreme precipitation thresholds associated to landslides in both regions. Firstly, two locations were chosen, within two areas prone to landslides and characterized by significantly different geomorphological settings, namely, SMA and SMP. Based on the DISASTER database, we showed that the seasonal cycle of months with higher landslide activity corresponded to the extended winter season between October and March, for the historical period defined (1971–2000). To quantify the relationship between extreme rainfall and landslide activity, the RTTs were calculated, and the rainfall lower-limit thresholds were selected. These thresholds were obtained for the specific locations and for four different timescales of consecutive days of accumulated precipitation (1D, 10D, 30D, and 60D).

The extreme precipitation assessment was achieved through statistical analysis, using the values of the percentiles 75th, 95th, 97.5th, 99th, and 99.9th from the consecutive days of accumulated precipitation series. A relatively large ensemble of 15 EURO-CORDEX models were used to simulate the historical and future precipitation series, and a multimodel ensemble was built, by considering that all models contributed equally. Subsequently, each model, and the multimodel, was evaluated against the IBO2 precipitation extremes, in order to analyze the models' performance at simulating extreme values. This analysis showed that the multimodel ensemble appeared to be one of the best representing models, with a good agreement at both locations, timescales, and percentiles.

To estimate the projected future changes in the extreme values of the four different timescale precipitation series, over the two locations, the historical simulated precipitation series were compared against the future simulated precipitation series, considering two RCP scenarios: RCP 4.5 and RCP 8.5. Also, the amount of precipitation associated to the RTTs' percentiles, for the end of the century, was obtained for each location and timescale and considering both RCP scenarios. It was observed, that in both locations, the higher the percentile and timescale, the wider spread the models revealed. Most models tended to overestimate the extreme precipitation at the daily timescale, whereas at the longer timescales, the majority tended to underestimate, albeit with some geographical differences as *SMP* showed the largest spread between models when compared to *SMA*. Also, in both locations, it was observed that as the consecutive days of accumulated precipitation increase, the RTTs' percentiles decrease.

A highlight of this work was the performance of the multimodel ensemble that stood out as one of the best representing models, and so, it was used as a base reference for future changes in extreme precipitation. The multimodel ensemble showed an increase of the extreme precipitation in both timescales, for the RCP 4.5 scenario and at 1D timescale for the RCP 8.5. However, when following the RCP 8.5 scenario at 10D, 30D, and 60D, it was projected a decrease of the extreme precipitation for *SMA*. According to this analysis, when following the RCP 8.5 scenario, suggests that the RTT for one intense day of precipitation, that may induce a landslide event, appears to be an event more likely by the end of the century. However, the RTTs for 10, 30, and 60 consecutive days of antecedent accumulated precipitation, over *SMA*, appear to correspond to events less likely by the end of the twenty-first century. Over *SMP*, when following the RCP 8.5, almost no significant change is projected. As for the RCP 4.5 scenario, the RTTs for one intense day of precipitation, and for 10, 30, and 60 consecutive days of antecedent accumulated precipitation, that may induce a landslide event, appear to become a more likely event by the end of the century.

Acknowledgements

This work was financed by national funds PIDDAC through FCT-Portuguese Foundation for Science and Technology, I.P., under the framework of the project BeSafeSlide — Landslide Early Warning soft technology prototype to improve community resilience and adaptation to environmental change (PTDC/GESAMB/ 30052/2017) and project Wex-Atlantic — Weather Extremes in the Euro Atlantic Region: Assessment and Impacts funded by FCT and FEDER (PTDC/CTA-MET/29233/2017, LISBOA-01-0145- FEDER-029233, NORTE-01-0145-FEDER-029233). Alexandre M. Ramos was also grateful to the Scientific Employment Stimulus 2017 - Fundação para a Ciência e Tecnologia (FCT, CEECIND/00027/2017). All IDL authors acknowledge FCT support through national funding (PIDDAC) – UIDB/50019/2020. To EEA-Financial Mechanism 2014-2021 and the Portuguese Environment Agency through Pre-defined Project-2 National Roadmap for Adaptation XXI (PDP-2) our gratitude for the data and collaborations. Last but not least the a special thank you to the climate modelling centers for the EUROCORDEX simulations and the free availability of the data (<https://www.euro-cordex.net/>).

Declarations

Conflict of interest The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Alvioli M, Melillo M, Guzzetti F, Rossi M, Palazzi E, von Hardenberg J, Brunetti MT, Peruccacci S (2018) Implications of climate change on landslide hazard in Central Italy. *Sci Total Environ* 630:1528–1543
- Belo-Pereira M, Dutra E, Viterbo P (2011) Evaluation of global precipitation data sets over the Iberian Peninsula. *J Geophys Res* 116. <https://doi.org/10.1029/2010JD015481>
- Cardoso RM, Soares PM, Miranda PM, Belo-Pereira M (2013) WRF high resolution simulation of Iberian mean and extreme precipitation climate. *Int J Climatol* 33:2591–2608. <https://doi.org/10.1002/joc.3616>
- Ferreira Ad, Zêzere JL (1997) Portugal and the Portuguese Atlantic Islands. In: Embleton C, Embleton-Hamann C (eds) *Dev Earth Surf Process* 5:391–407. [https://doi.org/10.1016/S0928-2025\(97\)80017-X](https://doi.org/10.1016/S0928-2025(97)80017-X)
- Garcia RAC, Oliveira SC (2020) Portugal landslide hazardscapes. In: Vieira G, Zêzere JL, Mora C (eds) *Landscapes and landforms of Portugal World Geomorphological Landscapes*
- Gariano S, Rianna G, Petrucci O, Guzzetti F (2017) Assessing future changes in the occurrence of rainfall-induced landslides at a regional scale. *Sci Total Environ* 596–597:417–426. <https://doi.org/10.1016/j.scitotenv.2017.03.103>
- Gariano SL, Verini Supplizi G, Ardzzone F, Salvati P, Bianchi C, Morbidelli R, Saltalippi C (2021) Long-term analysis of rainfall-induced landslides in Umbria, central Italy. *Nat Hazards* 106(3):2207–2225
- GERICS (2020) About EURO-CORDEX. Retrieved from EURO-CORDEX: <https://www.euro-cordex.net/060374/index.php.en>
- Giorgi F (1990) Simulation of regional climate using a limited area model nested in a general circulation model. *J Clim* 3:941–963. [https://doi.org/10.1175/1520-0442\(1990\)003<0941:SORCUA>2.0.CO;2](https://doi.org/10.1175/1520-0442(1990)003<0941:SORCUA>2.0.CO;2)
- Giorgi F, Mearns L (1991) Approaches to the simulation of regional climate change: a review. *Rev Geophys* 29:191–216. <https://doi.org/10.1029/90RG02636>
- Giorgi F, Mearns L (1999) Introduction to special section: regional climate modeling revisited. *J Geophys Res* 104:6335–6352. <https://doi.org/10.1029/98JD02072>
- Giorgi F, Jones C, Asrar G (2009) Addressing climate information needs at the regional level: the CORDEX framework. *Bull World Meteorol Org* 58:175–183
- Glade T, Crozier M, Smith P (2000) Applying probability determination to refine landslide triggering rainfall thresholds using empirical “Antecedent daily rainfall model.” *Pure Appl Geophys* 157:1059–1079. <https://doi.org/10.1007/s000240050017>

- Guha-Sapir D, Hoyois P, Below R (2012) Annual disaster statistical review 2011: The numbers and trends. Annual Disaster Statistical Review The numbers and trends
- Guzzetti F, Peruccacci S, Rossi M, Stark C (2007) Rainfall thresholds for the initiation of landslides in central and southern Europe. *Meteorol Atmos Phys* 98:239–267. <https://doi.org/10.1007/s00703-007-0262-7>
- Herrera S, Gutiérrez J, Ancell R, Pons M, Frías M, Fernández J (2012) Development and analysis of a 50-year high-resolution daily gridded precipitation dataset over Spain (Spain02). *Int J Climatol* 32:74–85. <https://doi.org/10.1002/joc.2256>
- Hurlimann M, Guo Z, Puig-Polo C, Medina V (2021) Impacts of future climate and land cover changes on landslides susceptibility: regional scale modelling in the Val d'Aran region (Pyrenees, Spain). *Landslides*. <https://doi.org/10.1007/s10346-021-01775-6>
- IPCC (2012) Managing the risks of extreme events and disasters to advance climate change adaptation. Special Report of the Intergovernmental Panel on Climate Change. <https://doi.org/10.1017/CBO9781139177245>
- IPCC (2014) Climate change 2014: synthesis report. Contribution of Working Groups I,II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland
- IPCC (2018) An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development
- IPCC (2021) Climate Change 2021: The Physical Science Basis. Contribution of working group I to the sixth assessment report of the Intergovernmental panel on climate change
- Jacob D, Teichmann C, Sobolowski S et al (2020) Regional climate downscaling over Europe: perspectives from the EURO-CORDEX. *Reg Environ Change*. <https://doi.org/10.1007/s10113-020-01606-9>
- Jacob D, Petersen J, Eggert B et al (2014) EURO-CORDEX: new high-resolution climate change projections for European impact research. *Reg Environ Change* 14:563–578
- Katragkou E, García-Díez M, Vautard R, Sobolowski S, Zanis P, Alexandri G, Jacob D (2015) Regional climate hindcast simulations within EURO-CORDEX: evaluation of a WRF multi-physics ensemble. *Geosci Model Dev* 8:603–618. <https://doi.org/10.5194/gmd-8-603-2015>
- Kotlarski S, Keuler K, Christensen O, Collette A, Déqué M, Gobiet A, Wulfmeyer V (2014) Regional climate modelling on European scales: a joint standard evaluation of the EURO-CORDEX RCM ensemble. *Geosci Model Dev* 7:1297–1333. <https://doi.org/10.5194/gmd-7-1297-2014>
- Kutiel H, Trigo R (2014) The rainfall regime in Lisbon in the last 150 years. *Theor Appl Climatol* 118:387–403. <https://doi.org/10.1007/s00704-013-1066-y>
- Laprise R (2008) Regional climate modelling. *J Comput Phys* 3641–3666. <https://doi.org/10.1016/j.jcp.2006.10.024>
- Leung L, Mearns L, Giorgi F, Wilby R (2003) Regional climate research: needs and opportunities. *Bull Am Meteor Soc* 84:89–95. <https://doi.org/10.1175/BAMS-84-1-89>
- Lin Q, Wang Y, Glade T, Zhang J, Zhang Y (2020) Assessing the spatiotemporal impact of climate change on event rainfall characteristics influencing landslide occurrences based on multiple GCM projection in China. *Clim Change* 162:761–779. <https://doi.org/10.1007/s10584-020-02750-1>
- Maraun D, Shepherd T, Widmann M et al (2017) Towards process-informed bias correction of climate change simulations. *Nature Clim Change* 7:764–773. <https://doi.org/10.1038/nclimate3418>
- Meinshausen M, Smith S, Calvin K, Daniel J, Lamarque M-F, Matsumoto K, van Vuuren D (2011) The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Clim Change* 109:213–241. <https://doi.org/10.1007/s10584-011-0156-z>
- Melo-Gonçalves P, Rocha A, Santos J (2016) Robust inferences on climate change patterns of precipitation extremes in the Iberian Peninsula. *Phys Chem Earth* 94:114–126. <https://doi.org/10.1016/j.pce.2016.05.003>
- Oliveira S, Zêzere J, Catalão J, Nico G (2015) The contribution of PSInSAR interferometry to landslide hazard in weak rock-dominated areas. *Landslides* 12(4):703–719. <https://doi.org/10.1007/s10346-014-0522-9>
- Pereira S, Garcia RA, Zêzere JL, Oliveira SC, Silva M (2017) Landslide quantitative risk analysis of buildings at the municipal scale based on a rainfall triggering scenario. *Geomat Nat Haz Risk* 8(2):624–648. <https://doi.org/10.1080/19475705.2016.1250116>
- Pereira S, Ramos A, Rebelo R, Trigo R, Zêzere J (2018) A centennial catalogue of hydro-geomorphological events and their atmospheric forcing. *Adv Water Resour* 98–112. <https://doi.org/10.1016/j.advwatres.2018.10.001>
- Pereira S, Zêzere JL, Quaresma ID, Bateira C (2014) Landslide incidence in the North of Portugal: Analysis of a historical landslide database based on press releases and technical reports. *Geomorphology*. <https://doi.org/10.1016/j.geomorph.2014.02.032>
- Prein A, Gobiet A, Truhetz H et al (2015) Precipitation in the EURO-CORDEX 0.11° and 0.44° simulations: high resolution, high benefits? *Clim Dyn* 46:383–412. <https://doi.org/10.1007/s00382-015-2589-y>
- Promper C, Gassner C, Glade T (2015) Spatiotemporal patterns of landslide exposure — a step within future landslide risk analysis on a regional scale applied in Waidhofen/Ybbs Austria. *Int J Disaster Risk Reduct* 12:25–33. <https://doi.org/10.1016/j.ijdrr.2014.11.003>
- Ramos A, Trigo R, Liberato M (2014) A ranking of high-resolution daily precipitation extreme events for the Iberian Peninsula. *Atmosph Sci Lett* 15:328–334. <https://doi.org/10.1002/asl2.507>
- Ramos A, Trigo R, Liberato M (2017) Ranking of multi-day extreme precipitation events over the Iberian Peninsula. *Int J Climatol* 37:607–620. <https://doi.org/10.1002/joc.4726>
- Reichenbach P, Cardinali M, De Vita P, Guzzetti F (1998) Regional hydrological thresholds for landslides and floods in the Tiber River Basin (central Italy). *Environ Geol* 35:146–159. <https://doi.org/10.1007/s002540050301>
- Santos J, Belo-Pereira M, Fraga H, Pinto J (2016) Understanding climate change projections for precipitation over western Europe with a weather typing approach. *J Geophys Res Atmos* 121:1170–1189. <https://doi.org/10.1002/2015JD024399>
- Santos M, Fonseca A, Fragoso M, Santos J (2019) Recent and future changes of precipitation extremes in mainland Portugal. *Theoret Appl Climatol* 137(1–2):1305–1319. <https://doi.org/10.1007/s00704-018-2667-2>
- Santos M, Fragoso M, Santos J (2017) Regionalization and susceptibility assessment to daily precipitation extremes in mainland Portugal. *Appl Geogr* 86:128–138. <https://doi.org/10.1016/j.apgeog.2017.06.020>
- Santos M, Santos J, Fragoso M (2015) Historical damaging flood records for 1871–2011 in northern Portugal and underlying atmospheric forcings. *J Hydrol* 530:591–603. <https://doi.org/10.1016/j.jhydrol.2015.10.011>
- Segoni S, Tofani V, Lagomarsino D, Moretti S (2016) Landslide susceptibility of the Prato–Pistoia–Lucca provinces, Tuscany, Italy. *J Maps* 12(1):401–406. <https://doi.org/10.1080/17445647.2016.1233463>
- Soares P, Cardoso R, Lima D, Miranda P (2017) Future precipitation in Portugal: high-resolution projections using WRF model and EURO-CORDEX multi-model ensembles. *Clim Dyn* 49:2503–2530. <https://doi.org/10.1007/s00382-016-3455-2>
- Soares P, Cardoso R, Miranda PM, Viterbo P, Belo-Pereira M (2012b) Assessment of the ENSEMBLES regional climate models in the representation of precipitation variability and extremes over Portugal. *J Geophys Res Atmosphere* 117. <https://doi.org/10.1029/2011JD016768>
- Soares P, Cardoso R, Miranda P, Medeiros J, Belo-Pereira M, Espírito-Santo F (2012c) WRF high resolution dynamical downscaling of ERA-Interim for Portugal. *Clim Dyn* 39:2497–2522. <https://doi.org/10.1007/s00382-012-1315-2>
- Soares PM, Cardoso RM, Miranda PM, Medeiros J d, Belo-Pereira M, Espírito-Santo F (2012a) WRF high resolution dynamical downscaling of ERA-Interim for Portugal. *Clim Dyn* 39:2497–2522. <https://doi.org/10.1007/s00382-012-1315-2>
- Trigo R, DaCamara C (2000) Circulation weather types and their influence on the precipitation regime in Portugal. *Int J Climatol* 20:1559–1581. [https://doi.org/10.1002/1097-0088\(200011\)20:13<1559::AID-JOC555>3.0.CO;2-5](https://doi.org/10.1002/1097-0088(200011)20:13<1559::AID-JOC555>3.0.CO;2-5)
- Trigo R, Ramos C, Pereira S, Ramos A, Zêzere J, Liberato M (2016) The deadliest storm of the 20th century striking Portugal: flood impacts and atmospheric circulation. *J Hydrol* 541:597–610. <https://doi.org/10.1016/j.jhydrol.2015.10.036>

- Trigo R, Valente M, Trigo I, Miranda P, Ramos A, Paredes D, García-Herrera R (2008) The impact of North Atlantic wind and cyclone trends on European precipitation and significant wave height in the Atlantic. *Trends and Directions in Climate Research* 1146:212–234. <https://doi.org/10.1196/annals.1446.014>
- Trigo R, Zêzere J, Rodrigues M, Trigo I (2005) The influence of the North Atlantic Oscillation on rainfall triggering of landslides near Lisbon. *Nat Hazards* 36:331–354. <https://doi.org/10.1007/s11069-005-1709-0>
- van Vuuren D, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, Rose S (2011) The representative concentration pathways: an overview. *Clim Change* 109:5–31. <https://doi.org/10.1007/s10584-011-0148-z>
- Vaz TCG (2021) Movimentos de vertente desencadeados pela precipitação em Portugal continental. PhD Thesis, Instituto de Geografia e Ordenamento do Território, Universidade de Lisboa
- Vaz T, Zêzere J (2016) Landslides and other geomorphologic and hydrologic effects induced by earthquakes in Portugal. *Nat Hazards* 81:71–98. <https://doi.org/10.1007/s11069-015-2071-5>
- Vaz T, Zêzere J, Pereira S, Oliveira S, Garcia R, Quaresma I (2018) Regional rainfall thresholds for landslide occurrence using a centenary database. *Nat Hazard* 18(4):1037–1054. <https://doi.org/10.5194/nhess-18-1037-2018>
- Wang Y, Leung L, McGregor J, Lee D, Wang W, Ding Y, Kimura F (2004) Regional climate modelling: progress, challenges and prospects. *J Meteorol Soc Jpn* 82:1599–1628. <https://doi.org/10.2151/jmsj.82.1599>
- Weigel A, Knutti R, Liniger M, Appenzeller C (2010) Risks of model weighting in multimodel climate projections. *J Clim* 4175–4191. <https://doi.org/10.1175/2010JCLI3594.1>
- Zêzere J (2000) Rainfall triggering of landslides in the area north of Lisbon. *Landslides in Research, Theory and Practice* 3:1629–1634
- Zêzere J, Rodrigues M (2002) Rainfall thresholds for landsliding in Lisbon area (Portugal). *Landslides* 333–338
- Zêzere J, Pereira S, Tavares A, Bateira C, Trigo R, Quaresma I, Verde J (2014) DISASTER: a GIS database on hydro-geomorphologic disasters in Portugal. *Nat Hazards* 72:503–532. <https://doi.org/10.1007/s11069-013-1018-y>
- Zêzere J, Trigo R, Trigo I (2005) Shallow and deep landslides induced by rainfall in the Lisbon region (Portugal): assessment of relationships with the North Atlantic Oscillation. *Natural Hazards and Earth System Science (NHES)* 5:331–344. <https://doi.org/10.5194/nhess-5-331-2005>
- Zêzere J, Vaz T, Pereira S, Oliveira S, Marques R, Garcia R (2015) Rainfall thresholds for landslide activity in Portugal: a state of art. *Earth Sci* 73:2917–2936. <https://doi.org/10.1007/s12665-014-3672-0>

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10346-022-01895-7>.

Joana R. Araújo · Alexandre M. Ramos (✉) ·

Pedro M. M. Soares · Ricardo M. Trigo

Instituto Dom Luiz, Faculdade de Ciências da Universidade de Lisboa, 1749-016 Lisbon, Portugal

Email: amramos@fc.ul.pt

Raquel Melo · Sérgio C. Oliveira

Centro de Estudos Geográficos, Instituto de Geografia e Ordenamento do Território, Universidade de Lisboa, Lisbon, Portugal

Raquel Melo

Departamento de Geociências, Escola de Ciências E Tecnologia, Universidade de Évora, Évora, Portugal

Sérgio C. Oliveira

Associate Laboratory TERRA, Lisbon, Portugal

Ricardo M. Trigo

Departamento de Meteorologia, Universidade Federal Do Rio de Janeiro, Rio de Janeiro 21941-919, Brazil