

Increasingly severe rainstorms put people and structures built on floodplains at risk

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Main findings

- Early warnings were issued across all three countries, enabling authorities to take timely action. Evacuations were carried out, where proactive measures helped limit the impact on communities at risk. As a result, the death toll remained low. While any loss of life is one too many, the combination of advance warning and decisive response significantly reduced the overall human cost of the event.
- Densely populated urban centres, particularly where tourism-driven development has expanded into floodplains, as well as highly exposed, low-lying, sandy and eroding coastal towns, faced particularly high levels of exposure. In Morocco, high exposure was further compounded by social vulnerability, with a number of people living in informal settlements where housing quality, infrastructure and access to services are often limited. These underlying exposure and vulnerability factors significantly increased the potential for impacts when the hazard occurred.
- Nine named storms have occurred since mid-January across the Mediterranean, affecting parts of both study regions. However, the overall return period of the Rx1day event over the two larger regions is not exceptionally high, at around 40 years in the southern region and approximately 5 years in the northern region. In contrast, at local scales the event corresponds to a much rarer occurrence, with return periods well in excess of 100 years.
- To estimate if human induced climate change influenced heavy rainfall over the region we first determine if there is a trend in gridded observations in Rx1day in both regions. Over the observational record since 1950, the intensity of the event shows an increase of about 36% in the southern region and approximately 29% in the northern region. In addition, variability associated with the North Atlantic Oscillation further amplifies extreme daily rainfall in the southern region, contributing an additional 5% to Rx1day intensity. In the northern region this influence is very small, with just about 2% increase in intensity.
- To assess the extent to which the observed changes can be attributed to human-induced climate change, we combine observational evidence with climate model simulations. While observations indicate an increase in intensity, the models in the southern region do not reproduce this trend. In the northern region, while the modelled trend is weaker, the difference between modelled and observed trends is smaller, with a combined increase in intensity of about 11%.

- Analysis of the atmospheric circulation from 4 February 2026 reveals a familiar North Atlantic pressure dipole, with lower sea-level pressure over the North Atlantic and northern Europe, and higher pressure over the subtropics and the Mediterranean. This pattern is associated with high precipitation across northern and northwestern Europe. The spatial structure of the event resembles similar circulation patterns found in the historical data considered, but they are weaker in magnitude compared to the 2026 event, highlighting no apparent trend, but that 2026 had a much less stable atmosphere and high moisture availability, leading to high winds and high rainfall.
- An additional analysis estimating how the number of heavy rainfall events above a threshold has changed shows indications of an increase in the number of the most extreme events, particularly in the northern region. However, the results are highly dependent on the exact region and dataset chosen.
- In summary, while all lines of evidence are highly uncertain, especially in the southern region, and exact numbers strongly depend on the region and dataset chosen, they point towards an increased intensity of especially the most extreme heavy rainfall events.
- Despite all countries having shown progress in strengthening disaster management systems at varying degrees, there is still a need to better align national and municipal level early warning and response systems and capacity building at local level.
- To reduce future flood risks, routinely updated disaster risk information needs to combine vulnerability assessments, exposure mapping and future climate projections. Planning decisions should then embed and enforce risk reduction across land-use planning, building codes, and infrastructure investment decisions.
- Long-term impacts of the current floods can also be reduced if response and early-recovery measures are timely and properly implemented. For example, assessing structural damage to homes, schools, roads and public buildings, safe contaminant clean-up and disposal, water and waste management system rehabilitation, preventive measles vaccination in displacement camps, among others.

1 Introduction

Since 16 January, nine named storms have battered the Mediterranean region, bringing torrential rain and high winds that forced the evacuation of more than 12,400 people in Spain, 3000 people in Portugal and 300,000 people in Morocco ([El Pais, 2026](#), [El País, 2026](#), [Reuters, 2026](#), [The Watcher, 2026](#)). The Spanish government has committed €7 billion in aid, including €2 billion for municipal infrastructure repairs and €2.1 billion to support agricultural holdings ([El Pais, 2026](#)). A further €1.78 billion has been committed by the Andalusian Regional Government, a region hit particularly hard. The Portuguese Government estimates that the direct costs of reconstruction will exceed €4 billion, in addition to €2.5 billion already issued in loans and incentives to aid reconstruction ([Reuters, 2026](#)), which was later revised to €3.5 billion ([Diário de Notícias, 2026](#)). The Moroccan government has

activated a restoration plan of about €280 million ([Reuters, 2026](#); [Atlas, 2026](#)).

On 28 January, Portugal saw four new extreme-rainfall records, including 50.3 mm in Leiria and 34.8 mm in Moncorvo. January 2026 was the third wettest January since 2000 in Portugal, with total precipitation about 1.5 times greater than the long-term average ([IPMA, 2026](#)). In Spain, exceptional rainfall was also reported in Grazalema (southern Spain): 581 mm fell in 24 hours on 5 February, and cumulative rainfall from 1 January to 9 February reached 2,527 mm, exceeding the previous record (~1,000 mm set in early 2009) by more than a factor of two ([El País, 2026](#)).

As a consequence, on 5 February, the aquifer system became clogged, forcing the evacuation of 1,500 residents for 11 days from the town of Cadiz ([El País, 2026](#)). In total, more than 115,000 inhabitants across 19 villages in the Sierra de Cádiz, in southern Spain, have been directly or indirectly affected by widespread road closures. Damage is estimated to cost between €15 and €20 million and expected to take up to three years to fully repair ([El País, 2026](#)). In Galicia, northwestern Spain, managing the series of storms has also been very challenging. Emergency services have dealt with more than 50,000 calls and over 7,600 weather-related incidents ([Cadena Ser, 2026](#)). Portugal's National Emergency and Civil Protection Authority (ANEPC) reported 7,517 weather-related incidents in mainland Portugal over six days (from Sunday to midday Friday, figures released on 6 February). The response mobilized 26,504 personnel and 10,505 ground assets. The report also notes aerial surveillance of major river systems, using five helicopters (two from the Portuguese Air Force and three operated under ANEPC) to track river flows in the most affected areas ([Rádio Comercial, 2026](#)).

In Spain, at least one person lost their life in the first of the storms, Storm Harry ([AEMET, 2026](#)). Six people have died in Portugal as a result of Storm Kristin, which produced winds of 202 km/h, classified as category 3 hurricane-force winds ([Euronews, 2026](#)). In total, 18 people have died in Portugal, directly or indirectly, as a result of the series of storms ([El País, 2026](#)). This wind speed far exceeded the previous record of 176.4 km/h recorded on 13 October 2018 during Storm Leslie. Storm Kristi left one million people without electricity or without homes. In addition, the storm caused widespread destruction, leaving many buildings without roofs, damaging stadiums, destroying aircrafts, and forcing the suspension of railway services. In Coimbra, a retaining wall collapsed, causing the Mondego River to overflow and washing away a section of the A-1 motorway, the country's main artery ([El País, 2026](#)).

The impact in northern Morocco has been even worse, with 43 deaths after some sites recorded almost a month's worth of rainfall in as little as three days and 300,000 people displaced ([The Watchers, 2026](#)). The Oued Makhazine dam surpassed its capacity by 60%, forcing it to release water gradually downstream. According to official figures, the floods have inundated 110,000 hectares of agricultural land ([Reuters, 2026](#)). Particularly the Safi Province was heavily impacted with the most severe impacts in Medina city, particularly the Bab Chaaba and Sidi Boudheb neighbourhoods. Similarly, the city of Ksar El Kebir in northwest Morocco was inundated, producing major disruptions to transport, electricity, water supply, and education systems ([Reuters, 2026](#)). These areas are characterized by very high urban density (up to 400 residents per hectare), older housing stock, and structural vulnerabilities ([Reliefweb, 2026](#)).

The nine storms affecting the region since January 16th are shown in Table 1 below, and daily rainfall from January 26th onwards in Figure 1.2. The series of storms was linked to a sequence of

low-pressure systems from atmospheric rivers that became stalled over the region, a pattern that is considered unusual. For the whole winter season, starting in September and ending in April, Pedro marks the 16th named storm of the season. The record stands at 17 ([AEMET, 2026](#)), making it likely that the historical maximum will be exceeded in the 2025–2026 season. While some of the storms also affected regions in Italy, France, Tunisia and Algeria, Spain, Portugal and Morocco were hit particularly hard. As a result, January 2026 was the wettest January recorded in Spain in the past 25 years, with rainfall reaching 119 mm—185% above the seasonal average ([Ministry for Ecological Transition and Demographic Challenge, 2026](#)). Between 20 January and 17 February 2026, Spanish national water reserves rose dramatically from 32,055 hm³ (57% capacity) to 46,229 hm³ (82.49%), the highest level ever recorded for this time of year since systematic records began in 1988 ([El Boletín Hidrológico, 2026](#)). In southern Portugal's Algarve region, at the end of January dam water reserves have increased from 48% to 89% compared to the same period last year ([Algarve Daily News, 2026](#)). With fuel dams, dam operators carried out large controlled discharges, releasing in about three days a volume of water comparable to Portugal's annual consumption ([Expresso, 2026](#)). Similarly, in Morocco, reservoir water levels have increased from 30% to 70% of capacity compared to the same period last year ([Morocco World News, 2026](#)).

In addition to extreme rainfall, strong winds contributed to many of the reported impacts. The 25-day period from 22 January to 15 February 2026 had the highest sustained high wind speed over time since measurements began in 1966 at Valencia Airport, Spain ([AEMET, 2026](#)). Multiple stations in eastern and northeastern Spain exceeded 119 km/h during Storm Oriana, classifying them as Category 1 hurricane-force winds on the Saffir-Simpson scale. In particular, Vilar de Canes in the east and Portbou - coll dels Belitres in the northeast reached 172 km/h, which is classified as category 2 ([AVAMET, 2026](#); [METEOCAT, 2026](#)). As a result of the strong winds caused by storm Oriana, one person died in Barcelona after being struck by a falling roof ([REUTERS, 2026](#)).

Storm	Date of naming
Harry	16 January
Ingrid	20 January
Joseph	25 January
Kristin	27 January
Leonardo	2 February
Marta	5 February
Nils	10 February
Oriana	11 February
Pedro	17 February

Table 1: Named storms affecting Spain and Portugal since the beginning of the year 2026. IPMA: Instituto Português do Mar e da Atmosfera. AEMET: Agencia Estatal de Meteorología

1.1 Meteorological conditions

The atmospheric circulation over the North Atlantic that led to these frequent storms was marked by persistent high-pressure systems. During the first weeks of the year, anticyclonic blockages over Greenland and the Scandinavian Peninsula diverted storms toward southern Europe ([AEMET, 2026](#)). In addition, the Azores High was positioned further south than usual, which favoured the arrival of

atmospheric rivers of moisture-laden air mass from the Atlantic, originating in the Caribbean (see Figure 1.1).

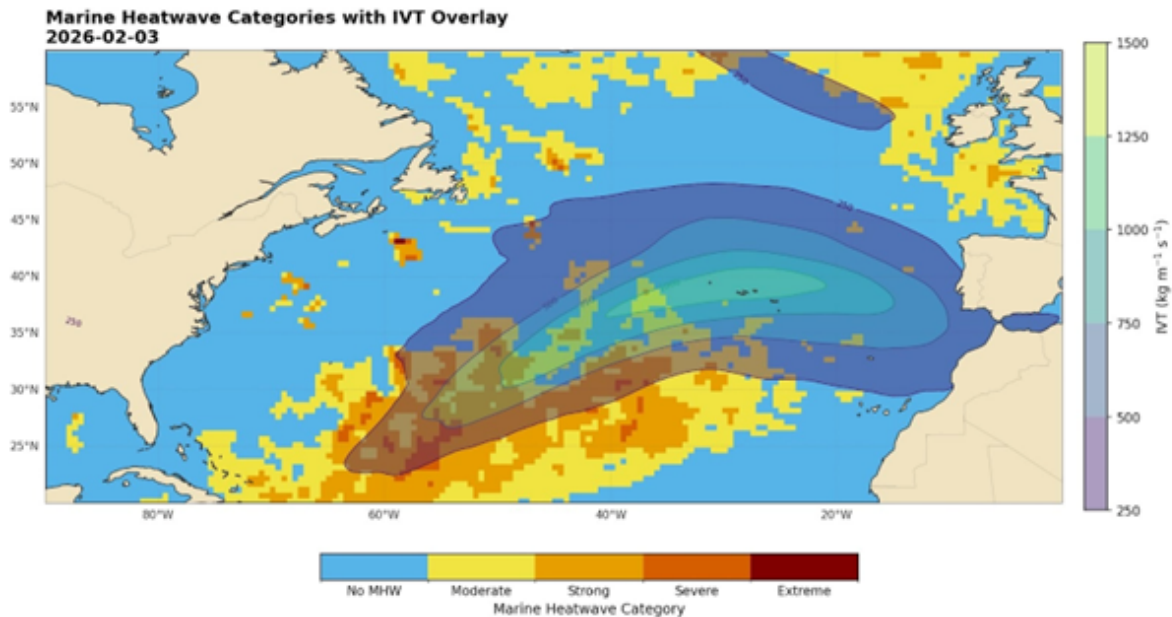


Figure 1.1: Marine heatwave categories based on the Climate Central attribution tool [Climate Shift Index: Ocean](#). The colours correspond to the severity of the marine heatwave, while the contours show the integrated vapour transport (IVT), a measure of the horizontal moisture transport from the surface. Figure courtesy of [Climate Central](#).

While the waters immediately surrounding Iberia and Morocco were not unusually warm, the atmospheric river drew moisture from a region of the Atlantic experiencing a strong to severe marine heatwave. The marine heatwave map in Figure 1.1 identifies areas where sea surface temperatures exceed the 90th percentile for at least five consecutive days, allowing for gaps of two days or less.

Importantly, all colored grid cells on the map also meet a high attribution threshold ([Climate Shift Index: Ocean](#)), with a probability ratio of at least 10. In other words, the observed marine heatwave conditions are at least ten times as likely in today's climate as they would have been in a pre-industrial climate without human-caused warming. Warmer ocean waters increase evaporation, adding more moisture to the atmosphere. When an atmospheric river taps into this unusually warm water, it can transport greater amounts of water vapor, increasing the potential for heavier rainfall over regions such as the Iberian Peninsula.

The possible link between the anticyclonic blockages that allowed the moisture transport and climate change is still an active area of research ([Ossó et al., 2025](#)). A theory is that these atmospheric conditions operate through interactions between the Arctic polar vortex and the jet stream. The Arctic polar vortex is a large, persistent area of low pressure and cold air that circulates counterclockwise around the North Pole in the stratosphere (about 16–48 km altitude). The jet stream, by contrast, is a fast-flowing band of winds in the troposphere (around 8–15 km high), typically located between 30°N and 60°N, which also circles the pole. When the polar vortex is strong and stable, the jet stream tends to shift further north and follows a straighter, less wavy path. ([Karpechko et al., 2022](#)). As the jet stream shifts to higher latitudes, Atlantic storms and associated moisture flows are diverted away from

their usual path towards the Mediterranean, causing the Mediterranean region, including the Iberian Peninsula and northern Africa, to dry out. Conversely, when the Arctic polar vortex weakens, it shifts, and sometimes the polar jet stream follows suit, becoming weaker or more undulating. This undulation causes the jet stream to reach lower latitudes, bringing more storms and moisture to the Mediterranean region.

Some recent observations show that the stratospheric polar vortex is tending to weaken and have more episodes of weak vortex ([Sevious, 2017](#)), although there is uncertainty as to whether global warming will make the polar vortex systematically stronger or weaker ([Screen et al., 2018](#)). The jet stream is controlled by the temperature gradient between the tropics and the poles. As anthropogenic warming is heating the Arctic more rapidly, this gradient weakens near the surface and tends to weaken and make the jet stream more wavy ([Francis and Vavrus, 2012](#)). In addition, the warming of the upper tropical troposphere and cooling of the polar stratosphere strengthen the gradient at altitude and tend to intensify and shift the upper jet stream towards the pole ([Ossó et al., 2025](#)). This causes a kind of struggle that influences the intensity and position of the jet stream, complicating predictions.

There are arguments for and against global warming favouring the series of storms in 2026. On the one hand, climate models predict a northward shift in the jet stream, which would reduce the total rainfall in the Mediterranean region, especially during the winter months ([Ossó et al., 2025](#)). On the other hand, the weakening of the jet stream due to fast Arctic warming would favour more persistent weather conditions, which would imply a higher probability of extreme events such as drought, flooding, cold waves, and heat waves ([Francis and Vavrus, 2012](#); [Kautz et al., 2022](#)). Thus, to understand whether any of these mechanisms can explain the sequence of consecutive storms observed in early 2026 needs further research and a better observational basis.

1.2 Extreme rainfall in western Spain, Portugal and Morocco

Precipitation in the Mediterranean is characterised by high spatial and temporal variability. Zittis et al. ([2021](#)) analysed spatial patterns in trends in extreme rainfall and total annual precipitation in the larger Mediterranean region in historical and RCP8.5 emission scenarios from 33 Euro-CORDEX models. The study found a north-south contrast in rainfall trends, with significant decreasing trends in rainfall extremes in the southern regions and increasing trends in the northern regions, although the annual total precipitation exhibits an overall decreasing tendency. Another study, this time based on 15 Euro-CORDEX climate models and focused on Spain, concluded that an increase in torrential rainfall (i.e. increased intensity and shorter duration) is expected in the coming decades under the RCP 4.5 and RCP 8.5 emission scenarios ([Requena et al., 2023](#)). A recent study based on the E-OBS database, which is a high-resolution, gridded, daily climate dataset, concluded that there was an increase in both droughts and extreme rainfall events in Spain between 1971 and 2022 ([Arellano et al., 2025](#)). However, a study using different weighted multi-model ensembles over Morocco showed a decrease of annual total precipitation from days exceeding the 95th percentile under RCP8.5 ([Balhane et al., 2022](#)). Therefore, while it seems likely that there has already been an increase in extreme rainfall events in northern Iberia - which will continue as greenhouse gas emissions continue - this is not expected to be the case uniformly across the whole of Iberia and north Africa.

Vicente-Serrano et al. ([2025](#)) demonstrated the dominance of internal variability, primarily North Atlantic Oscillation (NAO) and Mediterranean Oscillation (MO) over long-term trends on annual precipitation in the Mediterranean region, albeit with trends in sub-regions and sub-periods. The

assessment of changes in heavy rainfall in the Mediterranean in the latest IPCC report, AR6, shows low confidence in observed changes as well as their attribution and changes projected at 1.5°C of warming due to a lack of agreement in the observed and projected trends (Seneviratne et al., 2021). Only at 4°C of warming does a consistent increasing trend emerge with high confidence. This means that compared to other European regions, there is much higher uncertainty with respect to the impacts of climate change on heavy rainfall and thus a need for dedicated studies in specific regions. This is in contrast to the very clear and strong warming trend in the region and the drying during the summer months (e.g., [Cos et al., 2022](#)).

Studies published since AR6 focusing on regions within the Mediterranean, have found an increase in maximum precipitation in Spain ([Requena et al., 2023](#), [Calvo-Sancho et al., 2026](#)) and Portugal ([Araujo et al., 2022](#)), noting in particular that the heaviest rainfall increases in most regions studied by a factor larger than expected from the Clausius-Clayperon relationship alone (e.g., [Calvo-Sancho et al., 2026](#); [Barriopedro et al., 2025](#)). Although not in the same study region, a rapid attribution study on the extreme rainfall associated with Storm Daniel in 2023 that impacted Greece, Bulgaria and Türkiye found that such extreme rainfall spells were made more likely and intense due to climate change ([Zachariah, M. et al. 2023](#)). Recent studies also highlight the importance of multiple complementary methods to explore the human influence on events in the region in a comprehensive way. For instance, on a recent extreme convective event dynamically conditioned analysis found a clear thermodynamic influence on extreme rainfall while probabilistic approaches, which also encompass dynamical changes, gave highly uncertain results ([Barriopedro et al., 2025](#)).

Overall, the above literature underscores the complexity of rainfall patterns in the Mediterranean and the need for disentangling natural variability from long-term trends, for robustly analysing the role of climate change in extreme rainfall in the region. The strong influences of modes of variability such as the NAO may amplify (or weaken) the signals associated with global warming. In this study, we address this by including NAO as an additional covariate in our trend detection model, in addition to global mean surface temperatures (see Section A1).

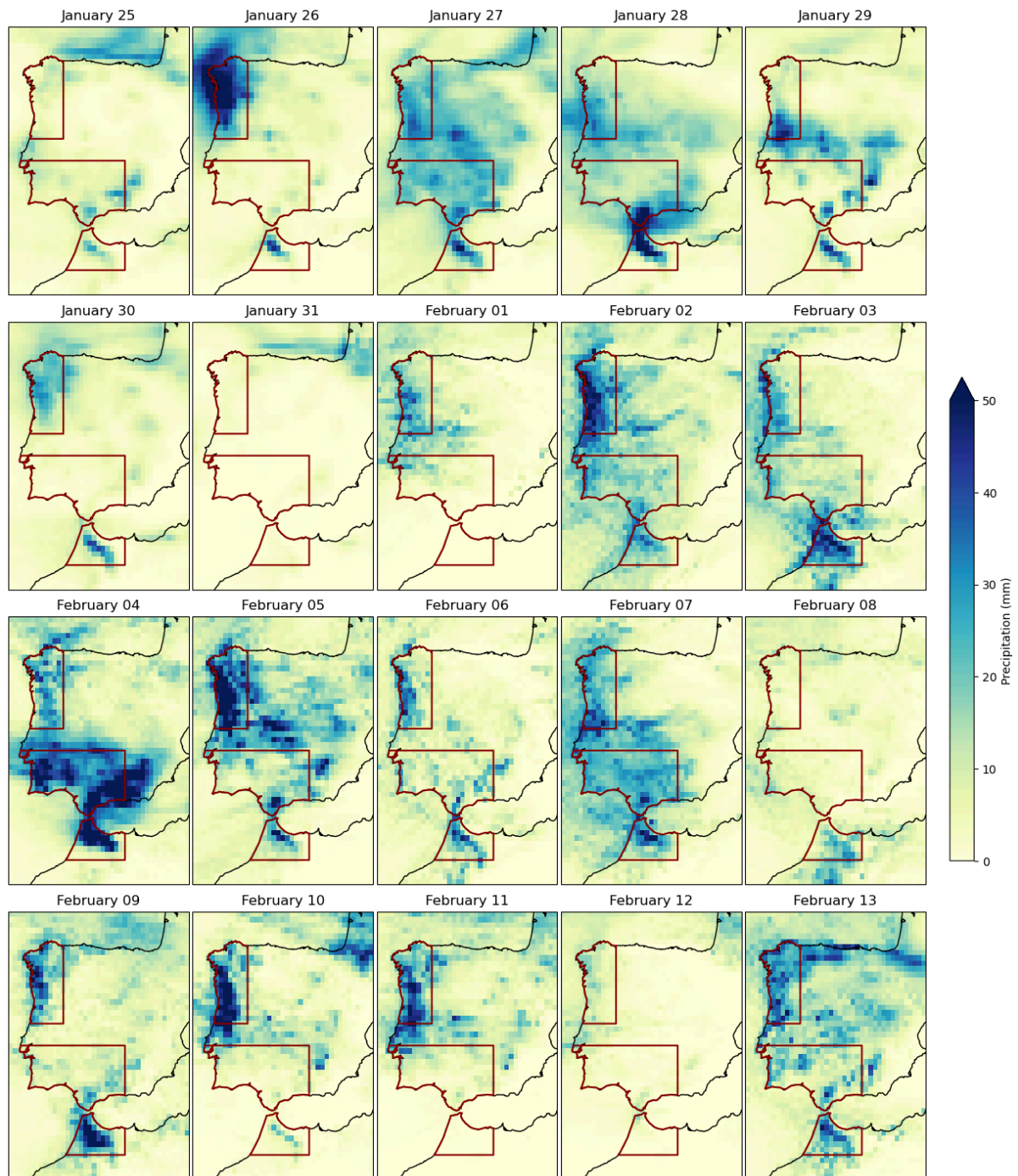


Figure 1.2: Maps of total daily precipitation from late January to mid February, showing the sequence of storms that made landfall in Spain, Portugal and northern Morocco. Dark red outlines show the two study regions (southern region crosses the Strait of Gibraltar). Data from ERA5.

1.3 Event Definition

The Iberian peninsula and northern Morocco were buffeted by a series of storms throughout January and February (Figure 1.2), leading to saturated soils that resulted in severe flooding during later downpours. To examine the effect of climate change on extreme rainfall in the region, we look at two separate regions that were severely impacted, outlined in red in Figure 1.2: a northern Iberian region from 40-44N, 9.5-7W; and a southern region from 34-39N, 10-3.5W. Figure 1.3 shows the local return periods of the most intense one-day event during this period in each region. Although similar amounts of rain fell in these regions on those days (Figure 1.2), the rain that fell in the northern region on this day is fairly typical for the region, with local return periods of less than five years; the rain that fell in the southern region is much more unusual relative to climatology, with local return periods of more than 100 years.

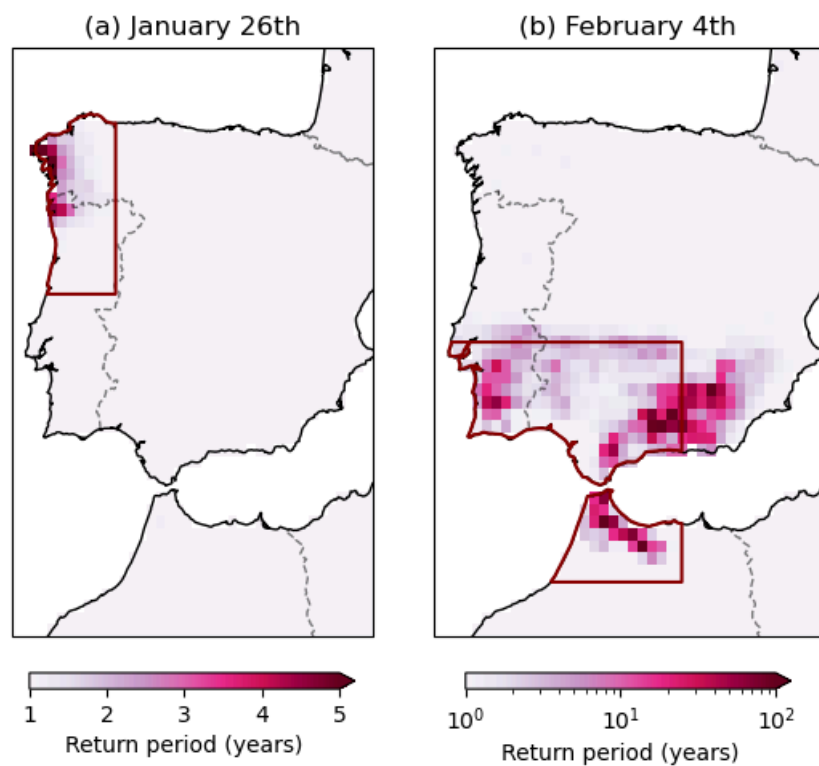


Figure 1.3: Maps of the local return period of the rainfall on selected storm days, using a statistical model fitted to each grid cell independently (ERA5): (a) January 26th; (b) February 4th. Dark red lines indicate the two study regions.

In this report we consider trends in annual maxima of one-day rainfall falling during the wetter months from October-March, denoted $Rx1day-ONDJFM$, in both regions. While this definition does not allow us to determine whether climate change has affected the frequency of similar storm events, it allows us to focus on changes in the most extreme rainfall, which are likely to be relevant for all storms in a sequence and so to have a compounding effect. Due to the known issues with representation of wind speeds in gridded data products, we do not attempt to attribute the extreme winds associated with the storms, only the precipitation.

We study the influence of anthropogenic climate change on extreme rainfall events in Iberia and Morocco by comparing the likelihood and intensity of similar extremes at present with those in a 1.3°C cooler climate. We also extend this analysis into the future by assessing the influence of a further 1.3°C of global warming from present. This is in line with the latest Emissions Gap Report from the United Nations Environment Programme, which shows that the world is on track for at least 2.6°C temperature rise given currently implemented policies ([UNEP, 2024](#)).

2 Observed trends

The observational analysis initially considered precipitation from five gridded data products: E-Obs, ERA5, CHIRPS, CPC, and MSWEP. However, CHIRPS and CPC were found to perform poorly at representing the recorded rainfall in both study regions, and so were excluded from further analysis. MSWEP is essentially a downscaling of ERA5 and, while it performed comparably in the region, we choose to include only the longer ERA5 dataset, to avoid double-counting information.

Note that because ERA5 was used to calculate the NAO covariate, the main model results presented here only use data from 1950 onwards, not the full E-Obs dataset from 1920-2026. The robustness of the results to the length of the dataset is discussed below.

2.1 Southern region

Figures 2.1 and 2.2 show the time series of Rx1day-ONDJFM (annual maximum daily precipitation from October-March) from 1950-2026 in the southern study region in ERA5 and E-Obs, with the fitted GMST-dependent trend overlaid. In both panels 2.1a and 2.2a the GMST-dependent trend (black line) closely resembles the nonparametric local regression (Loess) smoother fitted over time (green line), suggesting that this trend is well represented by the fitted model; in both datasets, the expected precipitation on the wettest October-March day is increasing with human-caused climate change, with around 23% more rain expected in the current climate than in a 1.3°C cooler climate in ERA5 (95% confidence interval: -0.3%, 48%) and around 49% more in E-Obs (24, 77%) (Table 2.1).

We also check the expected change when the NAO is not taken into account (Table A2.1); this also allows us to check the relationship between global warming and Rx1day in the full E-Obs time series from 1920-2026, and confirm that the increase in extreme rainfall is robust both to the inclusion of the NAO index and the length of dataset used.

Similarly, in panels 2.1b and 2.2b the relationship between the normalised DJF NAO index and Rx1day-ONDJFM is fairly well represented by the linear model, with negative values of the NAO index associated with wetter extremes than positive values. The current normalised NAO value of -0.8 is associated with 4-5% more rainfall than would be expected in a neutral phase. The full fitted model is shown in panels 2.1c and 2.2c.

The rainfall on February 4th 2026 was unusually intense, with an estimated return period of around 40 years in the current climate and given the current NAO state; however, because the event was so extreme the uncertainty about the return period is extremely high. In ERA5, the likelihood of

experiencing what is now approximately a one-in-40-year Rx1day event is an estimated 65 times higher than it would have been without human-caused warming, and in E-Obs, an estimated 48 times higher; however, the uncertainties about these numbers are also extremely high. The current NAO state is estimated to have increased the likelihood of similarly extreme rainfall by a factor of 1.4 to 2. All of these results are summarised in Table 2.1.

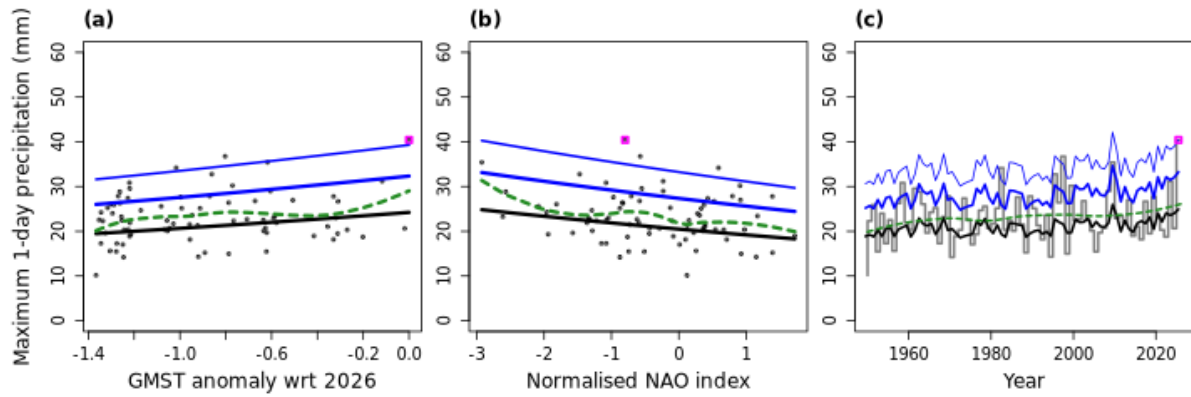


Figure 2.1: October-March Rx1day in the southern study region in ERA5, with fitted model overlaid: (a) expected values depending on GMST only, with NAO fixed at the mean value; (b) expected values depending on the NAO only, with GMST fixed at the mean value; (c) trend over time, given the observed values of the smoothed GMST and DJF NAO. In each panel, the solid black line denotes the expected rainfall on the wettest day each year; blue lines indicate the expected magnitude each year of a 1-in-6-year (thick line) and 1-in-40-year low rainfall event (thin line). Green dashed line is a nonparametric Loess smoother. 2025-26 value is highlighted with a magenta box.

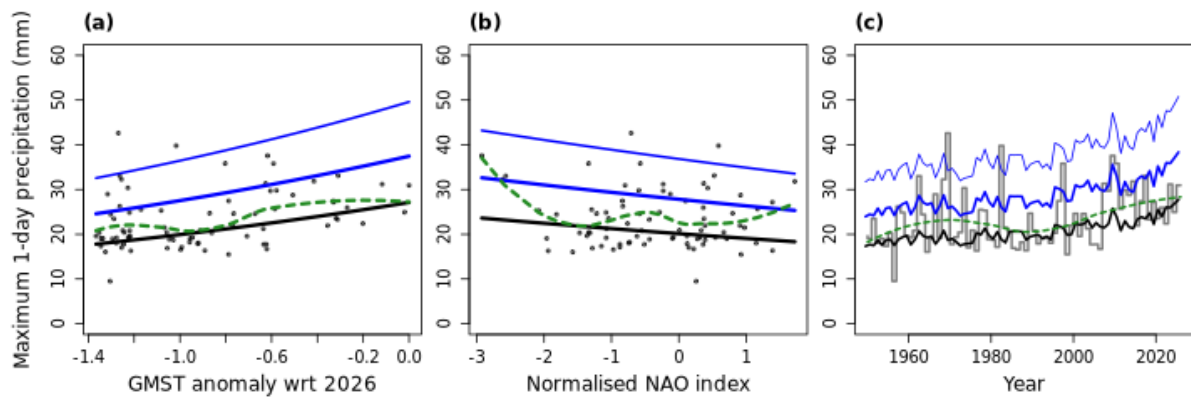


Figure 2.2: October-March Rx1day in the southern study region in E-Obs (1950-2026), with fitted model overlaid: (a) expected values depending on GMST only, with NAO fixed at the mean value; (b) expected values depending on the NAO only, with GMST fixed at the mean value; (c) trend over time, given the observed values of the smoothed GMST and DJF NAO. In each panel, the solid black line denotes the expected rainfall on the wettest day each year; blue lines indicate the expected magnitude each year of a 1-in-6-year (thick line) and 1-in-40-year low rainfall event (thin line). Green dashed

line is a nonparametric Loess smoother. The extreme rainfall in February 2026 was not captured in this dataset at the time of writing.

Figures 2.3 and 2.4 show the modelled change in return levels associated with a 1.3°C increase in GMST from the preindustrial to the current climate, and associated with the current NAO state, in ERA5 and E-Obs respectively. In all panels, the points representing Rx1day in each dataset transformed into the factual and counterfactual climates lie close to the lines representing the expected values, indicating that the statistical model represents the distribution of the data well. In panels 2.3a and 2.4a, there is a clear separation between the return levels in the current climate (red) and the past climate (blue), reflecting the strong increase in extreme rainfall associated with human-caused warming, while in panels 2.3b and 2.4b, the lines are fairly close together, reflecting the smaller contribution from the NAO. All of these results, along with the estimated return periods and changes in intensity for all datasets, are summarised in Table 2.1.

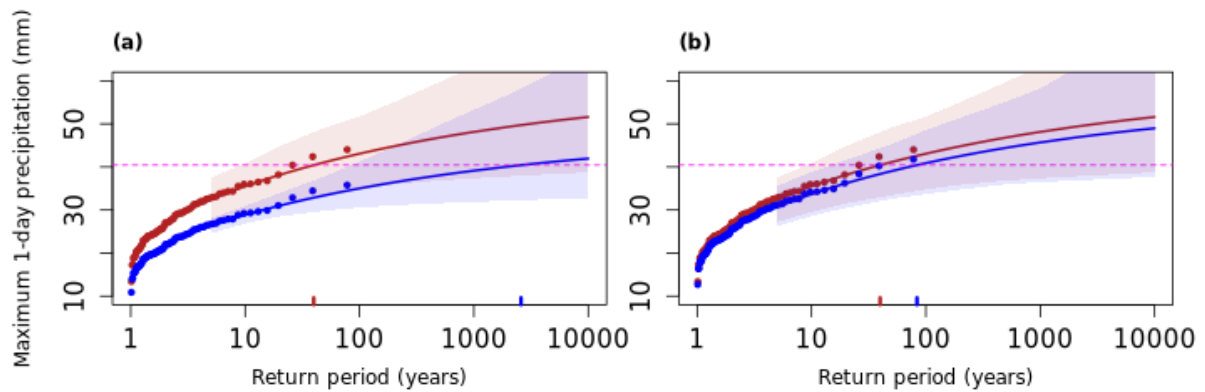


Figure 2.3: Expected return levels of Rx1day over the southern region in ERA5: (a) in the 2026 climate (red lines) and in a 1.3°C cooler counterfactual climate (blue line) and (b) given the December-January 2026 NAO state relative to a counterfactual neutral NAO state; all estimated from the statistical model described in section A1.3. Shaded regions represent 95% confidence intervals obtained via a bootstrapping procedure. The pink line shows the total rainfall observed on February 4th 2026. Red and blue ticks at the x axis indicate the estimated return level of the event in the 2026 climate and counterfactual climates.

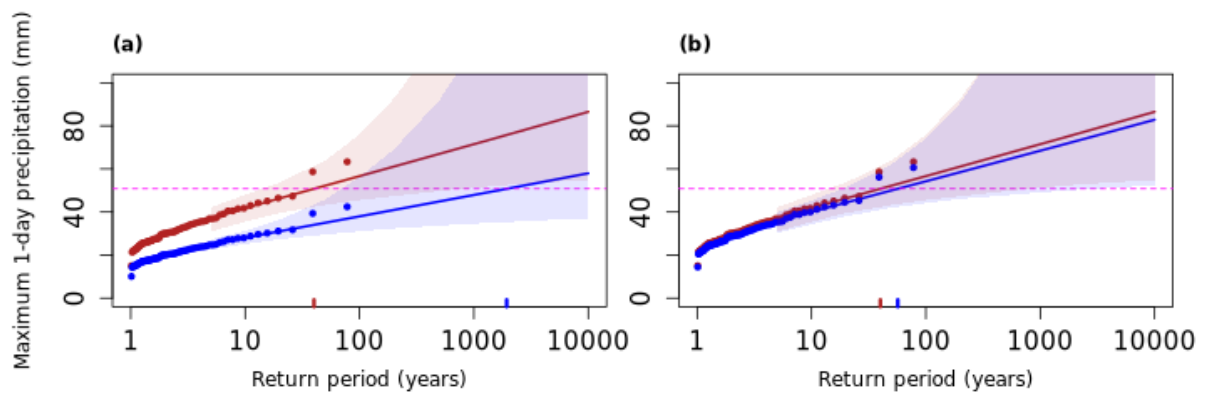


Figure 2.4: Expected return levels of Rx1day over the southern region in E-Obs: (a) in the 2026 climate (red lines) and in a 1.3°C cooler counterfactual climate (blue line) and (b) given the December-January 2026 NAO state relative to a counterfactual neutral NAO state; all estimated from

the statistical model described in section A1.3. Shaded regions represent 95% confidence intervals obtained via a bootstrapping procedure. Red and blue ticks at the x axis indicate the estimated return level of that event in the 2026 climate and counterfactual climates. The extreme rainfall in February 2026 was not captured in this dataset at the time of writing; pink line shows the expected magnitude of a one-in-40-year event in the current climate.

Dataset	Event magnitude (mm)	Return period	Change in intensity		Probability ratio	
			GMST	NAO	GMST	NAO
ERA5 (1950-) GMST + NAO	40.4	39.8 (8.99, Inf)	23 (-0.26, 47.7)	5.36 (0.66, 9.58)	64.9 (0.98, Inf)	2.1 (1.15, 29.2)
E-Obs (1950-) GMST + NAO	50.8*	40*	49.2 (23.6, 77.3)	4.44 (-1.13, 9.33)	48.4* (2.62, Inf)	1.42* (0.929, 4.57)

Table 2.1: Estimated return period (where available), change in intensity and change in likelihood (probability ratio) of the observed maximum rainfall in the southern region in ERA5 and E-Obs. For E-Obs, which does have coverage of the February 4th storm at the time of writing, a hypothetical 40-year event was used to estimate the expected event magnitude and the probability ratio (marked with *).

2.2 Northern region

Figures 2.5 and 2.6 show the time series of Rx1day-ONDJFM from 1950-2026 in the northern study region in ERA5 and E-Obs, with the fitted GMST-dependent trend overlaid. Again, we see that in panels 2.5a-b and 2.6a-b the fitted trend lines (black line) follow the nonparametric smoother (green line) closely, suggesting that this model captures the mean trend in Rx1day well, and that in both datasets, the expected precipitation on the wettest October-March day is increasing due to human-caused warming, with around 20% more rain expected in the current climate than in a 1.3°C cooler climate in ERA5 (95% confidence interval: -1%, 47%) and around 39% more in E-Obs (16%, 70%) (Table 2.2). Again, we also check the expected change when the NAO is not taken into account (Table A2.2), and when using the full length of the available E-Obs data, and find that the estimated trend is robust to these modelling choices. The NAO has less of an effect on rainfall intensity in this region than in the southern region, contributing only an additional 2-3%.

The wettest day of the 2025-26 season falls on different days in the two datasets: in E-Obs, on January 26th, and in ERA5, on November 13th, which was also identified as the wettest day in the southern region in the E-Obs dataset; the statistical approach used here models the magnitude of the wettest day each year regardless of when it occurs, although the results are expected to apply for any extreme rainfall event, with compounding impacts when such extreme events occur repeatedly. The wettest day in October-February 2025-26 was not particularly unusual in either dataset, with an estimated return period of three years in ERA5 and two years in E-Obs; for the attribution analysis described in Section 3 we use a return period of five years. Similarly extreme rainfall has been made an estimated

3-7 times more likely by human-caused warming, although the uncertainty on this number is high, particularly in ERA5.

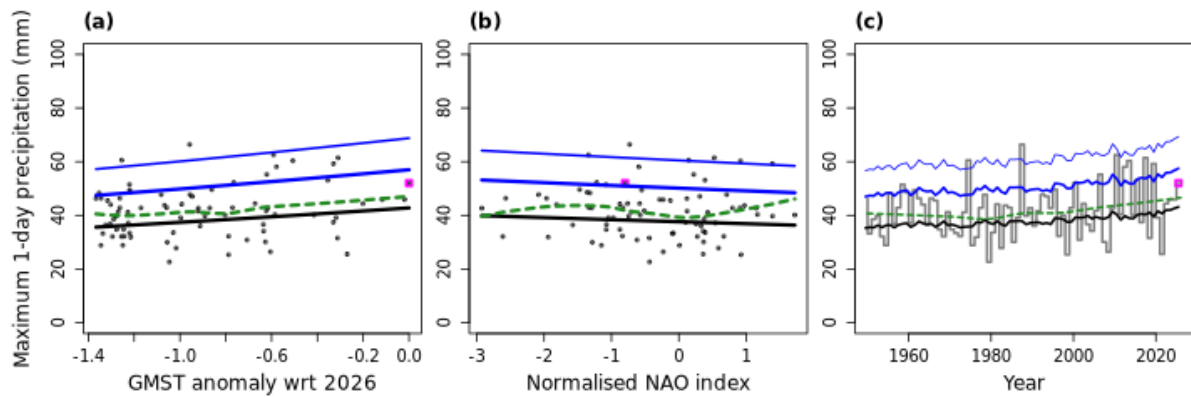


Figure 2.5: October-March Rx1day in the northern study region in ERA5, with fitted model overlaid: (a) expected values depending on GMST only, with NAO fixed at the mean value; (b) expected values depending on the NAO only, with GMST fixed at the mean value; (c) trend over time, given the observed values of the smoothed GMST and DJF NAO. In each panel, the solid black line denotes the expected rainfall on the wettest day each year; blue lines indicate the expected magnitude each year of a 1-in-6-year (thick line) and 1-in-40-year low rainfall event (thin line). Green dashed line is a nonparametric Loess smoother. 2025-26 value is highlighted with a magenta box.

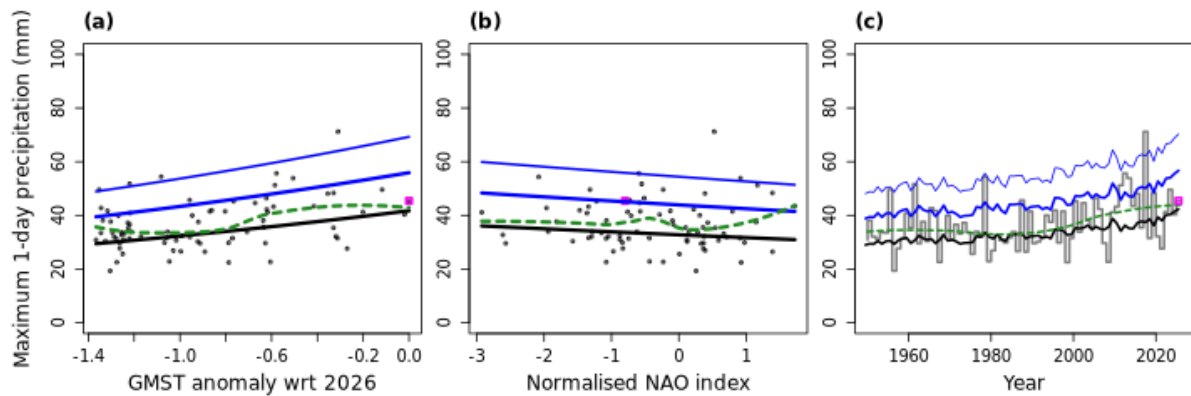


Figure 2.6: October-March Rx1day in the northern study region in E-Obs, with fitted model overlaid: (a) expected values depending on GMST only, with NAO fixed at the mean value; (b) expected values depending on the NAO only, with GMST fixed at the mean value; (c) trend over time, given the observed values of the smoothed GMST and DJF NAO. In each panel, the solid black line denotes the expected rainfall on the wettest day each year; blue lines indicate the expected magnitude each year of a 1-in-6-year (thick line) and 1-in-40-year low rainfall event (thin line). Green dashed line is a nonparametric Loess smoother. 2025-26 value is highlighted with a magenta box.

Figures 2.7 and 2.8 show the modelled change in return levels associated with a 1.3°C increase in GMST from the preindustrial to the current climate, and associated with the current NAO state, in ERA5 and E-Obs respectively. In all panels, the points representing Rx1day in each dataset

transformed into the factual and counterfactual climates lie close to the lines representing the expected values, indicating that the statistical model represents the distribution of the data well. Again, we see that in panels 2.7a and 2.8a, there is a clear separation between the return levels in the current climate (red) and the past climate (blue), reflecting the strong increase in extreme rainfall associated with human-caused warming, while in panels 2.7b and 2.8b, the lines are close together, reflecting the minimal contribution from the NAO to rainfall intensity. All of these results are summarised in Table 2.2.

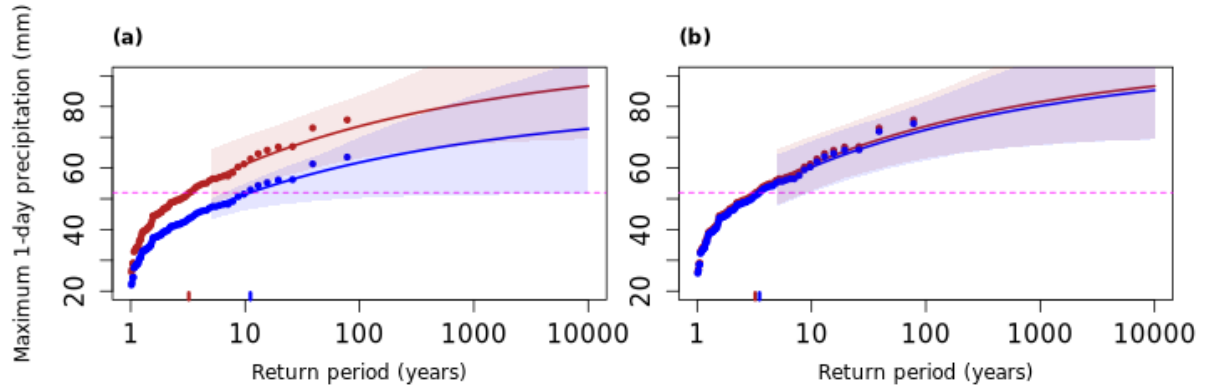


Figure 2.7: Expected return levels of Rx1day over the northern region in ERA5: (a) in the 2026 climate (red lines) and in a 1.3°C cooler counterfactual climate (blue line) and (b) given the December-January 2026 NAO state relative to a counterfactual neutral NAO state; all estimated from the statistical model described in section A1.3. Shaded regions represent 95% confidence intervals obtained via a bootstrapping procedure. The pink line shows the total rainfall observed on February 4th 2026. Red and blue ticks at the x axis indicate the estimated return level of the event in the 2026 climate and counterfactual climates.

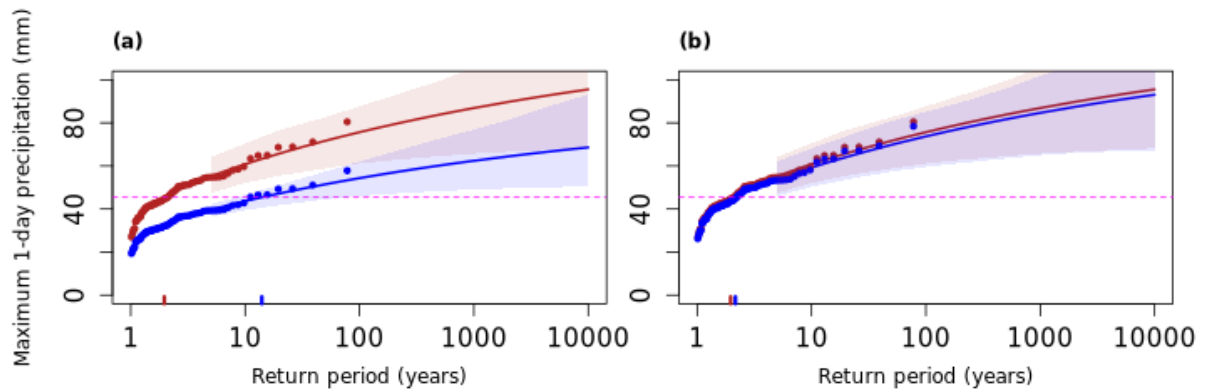


Figure 2.8: Expected return levels of Rx1day over the northern region in E-Obs: (a) in the 2026 climate (red lines) and in a 1.3°C cooler counterfactual climate (blue line) and (b) given the December-January 2026 NAO state relative to a counterfactual neutral NAO state; all estimated from the statistical model described in section A1.3. Shaded regions represent 95% confidence intervals obtained via a bootstrapping procedure. The pink line shows the total rainfall observed on February 4th 2026. Red and blue ticks at the x axis indicate the estimated return level of the event in the 2026 climate and counterfactual climates.

Dataset	Event magnitude (mm)	Return period	Change in intensity		Probability ratio	
			GMST	NAO	GMST	NAO
ERA5 (1950-) GMST + NAO	52	3.22 (1.56, 9.35)	19.1 (-1.01, 47.3)	1.61 (-1.75, 5.29)	3.45 (0.925, Inf)	1.09 (0.888, 1.36)
E-Obs (1950-) GMST + NAO	45.4	1.96 (1.29, 4.05)	39.3 (16.4, 70.5)	2.66 (-1.04, 6.67)	7.12 (2.71, 46.9)	1.1 (0.958, 1.35)

Table 2.2: Estimated return period (where available), change in intensity and change in likelihood (probability ratio) of the observed maximum rainfall in the northern region in ERA5 and E-Obs.

2.3 Trends in station data

Figure 2.9 highlights the difficulty of making general statements about trends in extreme rainfall in this region. The gridded trend is estimated using ERA5 data from 1950-2026, using the same statistical model as in sections 2.1 and 2.2, but here with parameters estimated at each grid cell, rather than over the rainfall averaged over each region. This analysis was then repeated for twenty stations from the GHCN-D network, using only those years with fewer than nine missing observations from October to March (meaning that more than 95% of observations were present), and only stations with more than 20 years of mostly complete data. Details of the stations used are given in Table 2.3.

In the northern region, the trends estimated from stations are broadly in agreement with those estimated from ERA5 data, with most stations showing an increase in the intensity of extreme rainfall events as the world warms. However, in the southern region, the majority of stations show a decrease in the intensity of Rx1day, in opposition to the region-wide trends estimated from ERA5, although Figure 2.9 also shows a mixture of drying and wetting trends within the study region. Investigation of the reasons for this is beyond the scope of this rapid study, but this corroborates the finding from much of the literature that trends in extreme rainfall in southern Spain and Portugal are expected to be mixed even in climatologically similar regions, so the effects of climate change may be difficult to detect and characterise using probabilistic methods alone.

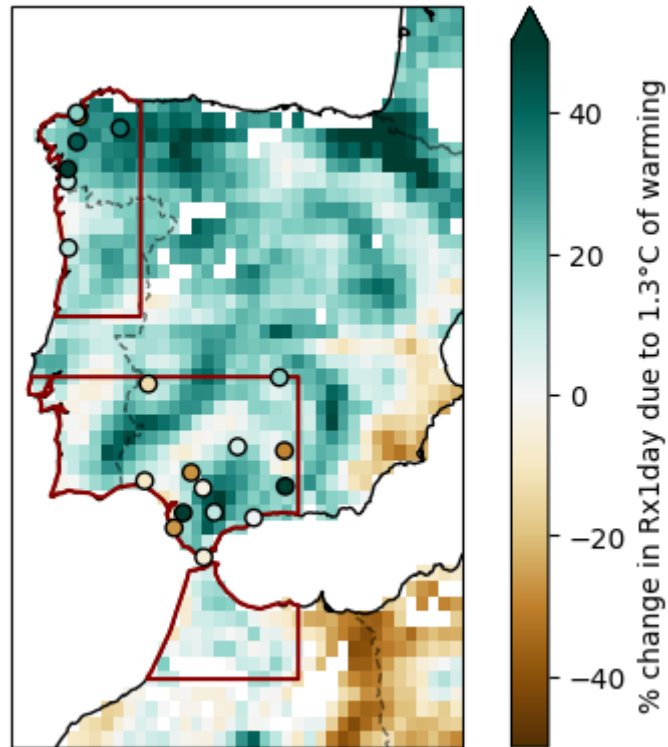


Figure 2.9: Map of estimated % change in Rx1day intensity associated with 1.3°C of warming, using a model fitted to each grid cell independently (ERA5). White indicates that the statistical model failed to converge. Points show the same trends estimated from GHCN-D station data within the two study regions.

Region	GHCN-D station name	Lon, lat	% change in intensity	N. years of data
Northern region	A_CORUNA_ALVEDRO	-8.37, 43.31	-34.18	25
	A_CORUNA	-8.42, 43.37	18.23	57
	LUGO_ROZAS	-7.46, 43.12	36.96	26
	PONTEVEDRA	-8.62, 42.44	49.24	37
	PORTO	-8.6, 41.13	12.63	69
	SANTIAGO_DE_COMPOSTELA_LABACOL	-8.41, 42.89	43.6	37
	VIGO_PEINADOR	-8.62, 42.24	10.35	52
Southern region	BADAJOS_TALAVERA_LA_REAL	-6.83, 38.88	-13.09	68
	CADIZ	-6.26, 36.5	-26.48	51
	CIUDAD_REAL	-3.92, 38.99	17.63	25
	CORDOBA_AEROPUERTO	-4.85, 37.84	7.26	60
	GRANADA_AEROPUERTO	-3.79, 37.19	50.24	51
	GRAZALEMA	-5.37, 36.76	11.25	20
	HUELVA_RONDA_DEL_ESTE	-6.91, 37.28	-9.12	29
	JAEN	-3.81, 37.78	-29.15	36
	JEREZ_DE_LA_FRONTERA	-6.06, 36.75	62.69	30
	MALAGA_AEROPUERTO	-4.49, 36.67	1.5	78

	MORON_DE_LA_FRONTERA	-5.62, 37.16	-3.16	66
	SEVILLA_SAN_PABLO	-5.88, 37.42	-27.25	40
	TARIFA	-5.6, 36.02	-5.97	30

Table 2.3: Details of GHCN-D stations used in the comparison of gridded trends. Change in *Rx1day-ONDJFM* intensity is estimated from a statistical model in which *Rx1day* depends on both *GMST* and the *NAO*.

2.4 Circulation analogues

The region was influenced by a succession of low-pressure systems similar to those shown in Figure 2.10a. The 4th of February was selected as the analogue day because of the substantial rainfall recorded on that date (see Section 1.2 and Methods Section A1.4). The 4th of February exhibits a characteristic North Atlantic sea-level pressure (SLP) dipole, with lower SLP over the North Atlantic and northern Europe and higher SLP over the subtropics and the Mediterranean. The composite analogues for the past (1950–1979) and present (1994–2023) periods show a generally weaker SLP pattern. In these composites, the subtropical high extends farther north and east, while the northern low in the 1994–2023 period is slightly displaced.

The rainfall event on the 4th of February is characterized by precipitation over southern parts of Portugal and Spain (Figure 2.10e). In contrast, the composite rainfall patterns for both past and present analogues show precipitation shifted to different locations, with higher rainfall in the north and reduced amounts in the south. This discrepancy arises because the rainfall associated with individual analogue days does not closely resemble that of the 4th of February (Figures A2.1 and A2.2). Relative to 1950–1979, the 1994–2023 period exhibits higher sea-level pressure over southern Europe and lower pressure over northern Europe, indicating a strengthened meridional pressure gradient (Figure 2.10d). This circulation change is dynamically consistent with increased precipitation over northern Europe and reduced precipitation over the Mediterranean region, as shown by the precipitation differences (Figure 2.10h). This suggests the event occurred in a background state already biased toward Mediterranean drying. These results should be interpreted with caution due to the fact the analogues of the 4th of February do not reproduce a hazard comparable in magnitude or structure to the event of interest (e.g. [Thompson, 2025](#)).

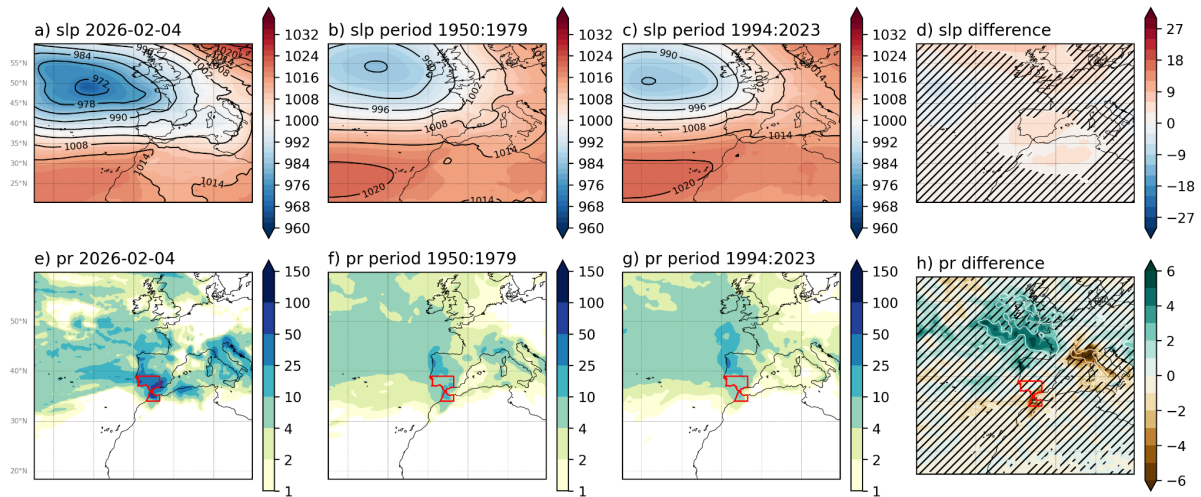


Figure 2.10: Changes in atmospheric analogues. (a) SLP (hPa) for the event, 4 February 2026. (b) Composite of the top 28 analogue days from the past period, 1951-1979. (c) Composite of the top 28 analogue days from the present period, 1994-2023. (d) Difference between the composites of past and present (present minus past). (e-h) as in a-d for the rainfall field (mm). SLP is used to identify analogues in all plots. Hashing signifies regions where the signal is not significant based on a two-sided t-test. Dark red line is the southern study region.

2.5 Summary of observed trends

Analysis of gridded rainfall products (ERA5 and E-Obs) shows a strong dependence of Rx1day-ONDJFM on GMST, with an estimated 23% to 49% more rainfall in the southern region and 20% to 39% more rainfall in the northern region associated with 1.3°C of human-caused warming. The current NAO state is expected to contribute an additional 4-5% on the wettest days in the southern region, but very little in the northern region (Sections 2.1 & 2.2). However, estimated trends are sensitive to both the region and the data source, with high uncertainty, and sometimes don't reflect the trends seen in station data (Section 2.3).

Analysis of the weather on days with similar circulation patterns to February 4th suggests that the observed circulation changes are dynamically consistent with increased precipitation over northern Europe and reduced precipitation over the Mediterranean region, although the pressure system on February 4th was unusual in both structure and intensity, meaning that no close analogues with rainfall similar to the event could be found in the historic record (Section 2.4).

3 Attribution of trends

3.1 Evaluation of climate models

In the subsections below, we show the results of the model evaluation for each location. The climate models are evaluated against the observations in their ability to capture:

1. Seasonal cycles: For this, we qualitatively compare the seasonal cycles of temperature and precipitation based on model outputs against observations-based cycles. We discard any models that exhibit ill-defined peaks in their seasonal cycles. We also discard the model if the rainy season onset/termination varies significantly from the observations.
2. Spatial patterns: Models that do not match the observations in terms of the large-scale precipitation patterns during the winter months of December-February are excluded.
3. Parameters of the fitted statistical models. We discard the model if the model and observation parameters ranges do not overlap.

In this study, we evaluated CORDEX and HighResMIP models (see appendix A1.2 for descriptions) on the three criteria listed above. The models are labelled as 'good', 'reasonable', or 'bad' based on their performances in terms of the four criteria discussed above. A model is given an overall rating of 'good' if it is rated 'good' for all four characteristics. If there is at least one 'reasonable', then its overall rating will be 'reasonable' and 'bad' if there is at least one 'bad'. We aim to use only 'good' models where possible, but for each framing or model setup we also include 'reasonable' models if we would otherwise retain five or fewer models for that framing. Furthermore, where more than one variant of a HighResMIP model passed validation, we retained only the better-performing model or, where two or more variants achieved the same score, the higher-resolution variant. Tables of the

model evaluation results can be found in Appendix A3. Tables of the model evaluation results can be found in Appendix A4.

3.2 Synthesis of results

For the two event definitions described above we evaluate the influence of anthropogenic climate change and the NAO on Rx1day heavy precipitation in both regions by calculating the probability ratio as well as the change in intensity using observations and climate models. Models which do not pass the evaluation described above are excluded from the analysis. The aim is to synthesise results from models that pass the evaluation along with the observations-based products, to give an overarching attribution statement. More details can be found in Otto et al. (2024). Tables of the results of this model fitting can be found in Appendix A4.

Figures 3.1 and 3.2 show the changes in probability and intensity for the observations (blue) and models (red). Before combining them into a synthesised assessment, a representation error is added (in quadrature) to the observations, to account for the difference between observations-based datasets that cannot be explained by natural variability. This is shown in these figures as white boxes around the light blue bars. The dark blue bar shows the average over the observation-based products, accounting for this representation error. Next, a term to account for intermodel spread is added (in quadrature) to the natural variability of the models. This is shown in the figures as white boxes around the light red bars. The dark red bar shows the model average, consisting of a weighted mean using the (uncorrelated) uncertainties due to natural variability plus the term representing intermodel spread (i.e., the inverse square of the white bars).

Observation-based products and models are combined into a single result in two ways. Firstly, we neglect common model uncertainties beyond the intermodel spread that is depicted by the model average, and compute the weighted average of models (dark red bar) and observations (dark blue bar): this is indicated by the magenta bar. As, due to common model uncertainties, model uncertainty can be larger than the intermodel spread, secondly, we also show the more conservative estimate of an unweighted, direct average of observations (dark blue bar) and models (dark red bar) contributing 50% each, indicated by the white box around the magenta bar in the synthesis figures. The results are also given in tables 3.1 and 3.2 for the two respective regions.

For the southern region we observe a strong increase in the intensity of Rx1day of about 36% (-3%, 87%), which is higher than expected just from the Clausius-Clayperon relationship alone, but in line with some recent studies reviewed in Section 1.1. The climate models that pass the evaluation do not represent this observed trend and show a very small increase in likelihood and intensity when synthesised, with a weighted synthesis of about 8% (-13%, 36%) of increase in intensity but just over 1% (-15%, 22%) for the models alone.

The influence of the NAO is consistent between observations and models, showing an increase in the intensity of about 5% (-1%, 11%). The corresponding changes in likelihood can be found in table 3.1.

For the northern region we find a similarly strong increase in the intensity in observations of about 29% (-3%, 74%). However, the climate models do represent this increasing trend as well, albeit

weaker, with a synthesised model result of a 6% (-8%, 25%) increase in intensity resulting in a weighted synthesis of 11% (-8%, 36%). The influence of the NAO is negligible in this region, but consistent again across models and observations by about 2% (-2%, 7%).

Data	GMST			NAO	
		Probability ratio	Intensity change (%)	Probability ratio	Intensity change (%)
Observations	Past-Present	56.1 (1.57, 2410000)	35.5 (-2.94, 86.8)	1.73 (0.819, 12.6)	4.9 (-0.384, 9.64)
Models		1.01 (0.203, 50.6)	1.19 (-15.1, 22)	1.01 (0.203, 50.6)	5.53 (-2.01, 14.1)
Synthesis (Weighted)		1.71 (0.236, 345)	8.36 (-13.3, 35.8)	1.56 (0.585, 18.7)	5.08 (-0.939, 11.1)
Synthesis (Unweighted)		7.54 (0.471, 23200)	17.1 (-10.3, 52.3)	1.32 (0.378, 29.4)	5.22 (-1.3, 12.1)
Models only	Present-Future	1.18 (0.398, 3.49)	1.57 (-9.32, 12.8)		

Table 3.1: Summary of results for attributable changes in Rx1day-ONDJFM in the southern region, presented in Figs 3.2 and A2.4: changes associated with (a) 1.3°C of warming from the preindustrial climate to 2026 (past-present), (b) the current NAO state compared to a neutral NAO state, and (c) a further 1.3°C of warming (present-future, using climate models only). The synthesised results are highlighted in purple.

The observational dataset used for the analysis, E-Obs, is a high quality dataset based on actual station data. It is therefore more reliable than reanalysis in the regions assessed. Whilst the number of stations has increased in the last few decades, increasing uncertainty, the quality control is high. Furthermore, the results found in E-Obs in the northern region are similar to those obtained for individual stations (Section 2.3). We therefore assume that a large part of the strong observed trends are driven by human-induced climate change and the changing number of stations only plays a minor role. In the southern region, stations and different data products give very different results (see Section 2.3).

As the difference between the climate models and observations are considerable, and in the southern region even qualitatively in many models, a robust quantification of the role of climate change in Rx1day in the two regions is difficult, if not impossible in the southern region. This is further highlighted by the inconsistency in model response between present and future warming, with some models showing an increase attributable to climate change in the past but not in the future, and vice versa. For the northern region, where the differences are smaller and consistent across all observational products, we communicate the weighted synthesis, mainly for consistency with other studies, but note that this is probably an underestimation compared to the unweighted results.

Data		(a) GMST		(b) NAO	
		Probability ratio	Intensity change (%)	Probability ratio	Intensity change (%)
Observations	Past - Present	4.96 (1.08, 108)	28.8 (-3.01, 73.9)	1.1 (0.922, 1.35)	2.13 (-1.67, 6.26)
Models		1.34 (0.543, 10.2)	6.49 (-8, 25.3)	1.34 (0.543, 10.2)	2.32 (-2.02, 7)
Synthesis (Weighted)		1.96 (0.64, 21.2)	11 (-7.75, 35.7)	1.1 (0.893, 1.54)	2.22 (-1.83, 6.59)
Synthesis (Unweighted)		2.58 (0.738, 35.1)	17.1 (-6.54, 49.1)	1.21 (0.632, 5.13)	2.23 (-1.85, 6.64)
Models only	(c) Present - Future	1.3 (0.862, 1.92)	4.42 (-1.77, 10.6)		

Table 3.2: Summary of results for attributable changes in *Rx1day-ONDJFM* in the northern region, presented in Figs 3.2 and A2.4: changes associated with (a) 1.3°C of warming from the preindustrial climate to 2026 (past-present), (b) the current NAO state compared to a neutral NAO state, and (c) a further 1.3°C of warming (present-future, using climate models only).

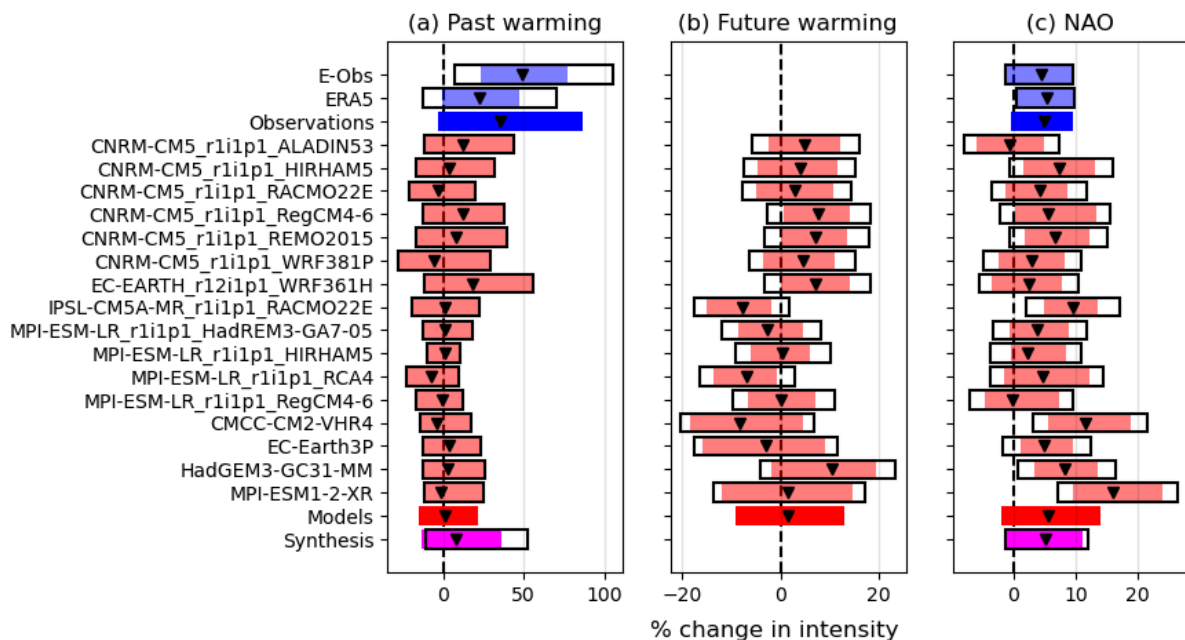


Figure 3.1: Synthesis of relative changes in *Rx1day-ONDJFM* in the southern region when comparing (a) the 2026 climate and a 1.3°C cooler climate representing the preindustrial past; (b) the 2026 climate and a 1.3°C warmer climate; (c) the 2026 NAO state and a neutral NAO state. Corresponding plots for probability ratios can be found in Appendix A2.3.

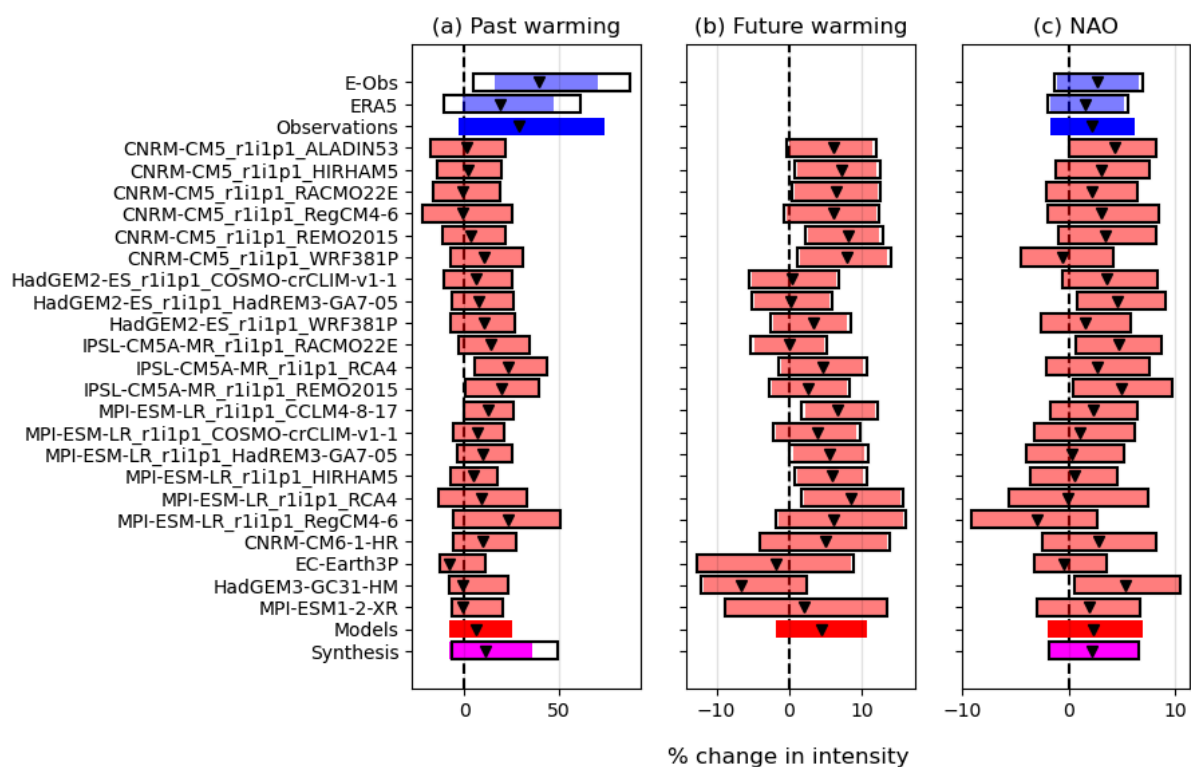


Figure 3.2: As figure 3.1, but for the northern region.

3.3 Conclusions

Combining lines of evidence from the synthesis results of the past climate, physical knowledge, the strong increase in observations, the fact that in both regions there are stations where the most extreme events increase in numbers (see Section 2.3) we communicate the best estimate of the observation-based result in both regions, but only a synthesised overarching attribution result of the change in intensity of 11% in the northern region. We do not quantify the attributable change in intensity in the southern region, but highlight that the lines of evidence assessed point to an increase in intensity with human-induced climate change.

4 Vulnerability and Exposure

Between mid-Jan and early February, six Atlantic storms struck the Mediterranean region - starting with storm Harry over 16-23 January and closing with storm Oriane during 12-16 February. An unusual concentration of hazards over a short period, the storms combined intense wind gusts with storm surges (up to 202 km/h and 13m, respectively, with storm Kristin) and heavy rainfall (up to 672 mm in 1.5 days with storm Leonardo) ([Al Jazeera, 2026](#); [Bett, 2026](#)). The rapid succession of storms left soils saturated, lowering infiltration capacity and magnifying risk of surface runoff, floods, and landslides.

Across the storm sequence, flooding and landslides led to several dozens of fatalities and injuries, including during debris removal. Widespread infrastructure damage led to road and rail closures, prolonged power and telecommunications outages affecting thousands, school shutdowns, and agricultural losses amounting to millions of euros. Tens of thousands were evacuated as winds felled trees and damaged buildings.

4.1 Sociodemographics

Although **Spain** ranks higher (HDI: 0.918) than the European average (HDI: 0.897) in terms of Human Development Index ([HDI](#)), severe material and social deprivation is high in southern Spain ([Eurostat, 2024](#)). In addition, in Southwestern Spain, the residents and tourists in highly urbanised low-lying coastal towns of Andalusia, especially along the Andalusian Mediterranean coast and the Gulf of Cádiz, living along ephemeral streams and floodplains affected by flash floods, are highly exposed to Mediterranean storms ([Mateos et al., 2023](#)). An analysis reveals that storms caused shoreline changes due to storm-driven erosion in the southern Gulf of Cádiz, which poses risks to the residents, businesses, and tourists at seafront housing, promenades, and critical services where many residents, visitors, and tourists concentrate ([Pueg et al. 2016](#)).

A social vulnerability analysis of the Spanish Mediterranean coast shows that the elderly, low-income individuals, and social marginalisation are at greater risk of extreme weather events, such as storms ([Morales et al., 2021](#)). Rural and peri-urban residents, commuters, and employees at industrial or logistics areas in flood corridors of southwestern Spain are also highly vulnerable, as Mediterranean storms can isolate these areas and impact emergency response capacity ([Barrionuevo et al., 2022](#)). Long-term immigration- and tourism-led urbanisation along the Andalusian coast is exposing people and assets in highly risk zones to Mediterranean storms and compound flooding, thereby amplifying impacts and the potential for future displacement ([Berkeley., 2025](#)).

Portugal has the same HDI (0.89) as the European average, and similar to Spain, the population in the coastal urban and peri-urban areas of Northern Portugal, are considered highly vulnerable to extreme weather events, including storms, storm-induced flooding, and erosion ([Cunha et al., 2021](#)). The residents and businesses in Southern Portugal, particularly in low-lying, sandy, and eroding coastal towns, as well as rural inland populations, particularly in areas where artificial protection such as dykes, seawalls, and nourished beaches is lacking, are highly vulnerable to extreme weather events

such as storms ([Lemos et al., 2024](#)).

Older adults (65+), particularly in urban centres like Porto, where the ageing ratio is 216.5 older adults per 100 youth, face increased risks of storm-related injuries and secondary health impacts ([Silva et al., 2024](#)). Children and immunosuppressed individuals are vulnerable as they are less physiologically resilient to extreme events. Low-income and socio-economically deprived communities, such as 6.5% households in Porto, experience compounded risk due to substandard housing and limited recovery capacity ([Silva et al., 2024](#)). Rural island populations in the north and central-east are highly susceptible to climate-induced hazards due to lower education levels, lower incomes, ageing populations, and lower population density, resulting in poorer access to services and institutions ([Grosso et al., 2015](#)).

Storms and resulting river and coastal floods lead to temporary displacements and evacuations in northern Portugal, particularly in coastal cities such as Porto and Ovar, and in river valleys in the north-central region ([Le Monde 2026](#)). There is no robust evidence about the long-lasting migration flows out of the region; residents return once the waters recede and repairs are made ([EEA, 2025](#)). Studies show that rapid population growth, immigration, and tourism-driven coastal development can exacerbate the impacts of storms, as more people are exposed to projected extreme water levels and dune/beach erosion during future storms and sea-level rise. ([Santos et al. 2024](#)).

Morocco has a lower HDI (0.71) than Spain and Portugal and residents, workers and tourists in the coastal zones in Morocco face a similar threat to storm-driven flooding. The recent floods affecting low income, rural and peri-urban areas in Northern Morocco, displaced a population of over 188,000 people who have been sheltered in tent camps, and reception shelters such as schools, community centres ([Africanews, 2026](#)). People living in these areas are more vulnerable to disasters due to higher illiteracy rate, higher proportions of children and elderly population, and limited access to basic services ([Agharroud et al., 2023](#)). They tend to live in neighbourhoods near drainage paths and low-lying zones, and have lower risk awareness and weaker coping strategies ([Salhi et al., 2024](#)). The socially marginalised groups in Morocco, the indigenous populations, often live in poorer, peripheral regions and have weaker social networks and less government support, making them highly vulnerable ([Noureddeen, 2023](#)). Women and those with lower levels of education, low-income workers, and those who cannot relocate or invest in structural protection, face limited options for avoiding or managing risks to extreme events ([Salhi et al. 2024](#); [Ouakkas et al., 2025](#)). Furthermore, the timing of the displacement coincides with the holy month of Ramadan, making it challenging for Moroccan flood evacuees living in overcrowded, unelectrified tent camps. Fast-breaking meals in the evening have become scarce and difficult to prepare ([AFP, 2026](#)).

4.2 Health

Recent floods in Spain, Portugal, and northern Morocco have caused limited fatalities but notable physical health burdens, including injuries caused by contact with objects in floodwater, hyperthermia and electrical injuries ([EEA, 2024](#)). Studies show that flooding creates conditions conducive to the proliferation of various pathogens (such as E coli and salmonella) significantly increasing the risk of epidemics and outbreaks ([Baba, 2025](#)). For example, flooding in the municipality of Grazalema, Spain overwhelmed sewage systems, heightening the risk of gastrointestinal infection and contaminated

water usage ([Reuters, 2026](#); [Artiles, 2024](#)). In addition, displaced populations, especially those living in displacement camps, are highly susceptible to additional forms of disease outbreaks such as measles ([Kouadio, 2010](#)). The European Centre for Disease Prevention and Control continues to monitor flood-affected areas, but as of publishing of this study, has not reported any flood or storm related outbreaks in Portugal or Spain ([ECDC, 2026](#)). Similarly no outbreak is reported in Morocco by the World Health Organization WHO Mediterranean regional office ([WHO, 2026](#)).

During flood events media attention and emergency response can tend to focus on physical loss of property, damaged infrastructure and mortality ([Lechheb, 2026](#)). Yet they can have immediate mental health impacts on both adults and young people. It has been reported that youth and children are more susceptible to an increased sense of fear, stress and hopelessness following flooding events ([Makwana, 2019](#)). Over the longer term youth also have an increased risk of developing, amongst others, mental health issues, depression and behavioral difficulties ([Acamh, 2025](#)). The need for psychological support is particularly important amongst vulnerable groups, such as women who often have increased responsibilities, the elderly who may struggle more with sudden changes, and displaced populations who have fewer opportunities for livelihood recovery and are more susceptible to repeated hazard events ([TheFloodhub, 2022](#), [Lechheb, 2026](#)).

4.3 Economic capacity and livelihoods

In Southwestern **Spain**, the livelihoods and economy are dominated by agriculture, including greenhouse horticulture, livestock grazing in dehesa agroforestry systems, mining of metallic ores such as copper and zinc, and ancillary tourism/public services ([OECD, 2021](#); [AKIS, 2026](#)). A sequence of storms and floods has caused catastrophic damage to crops, particularly orchards, winter vegetables, and greenhouse production, at a critical stage of the season. Andalusia's regional agriculture authority has estimated a potential loss of around 20 per cent of the region's agricultural output, which could affect the domestic supply chain and exports ([Urbancsek, 2026](#)). The Spanish Association of Olive Municipalities (AEMO) has projected a decrease of 170,000 tons in olive oil production for the 2025 -26 crop year compared to the same period in the previous harvest, which began in October. Additionally, producer groups have estimated that at least 50,000 tons of potential olive oil production have already been lost in the province ([Dawson, 2026](#)).

The northern region of **Portugal** has a highly diverse economy with a strong tourism and manufacturing base ([Focus Economics](#)). The storm has caused huge economic loss in the region, with extensive damage to factories and business parks. Some factories are completely damaged and inoperable, and others have had to pause production and operations for several days, resulting in direct economic losses and delays in production and logistics ([Gillespie, 2026](#)). It has been reported that more than 450 high-tension power lines collapsed, worsening the impact on the region's economic activities. ([Gillespie, 2026](#); [Lusa, 2026](#)). Local reports from Meirinhas (Pombal municipality) describe 95% of homes damaged and ceramics suppliers alone suffering about 40 million euros in losses ([Lopes, 2026](#)). The post-storm direct reconstruction cost has been estimated to be more than 4 billion euros ([Energy News, 2026](#)). The insured loss in Portugal due to the storm has been estimated between 300 million euros and 450 million euros ([Cotality 2026](#)).

The storm caused catastrophic forest damage, with significant losses in Leiria National Forest,

estimated at around 70% of the forest cover in the Ferreira do Zêzere municipality ([Santos et al. 2026](#)). The loss in the agriculture and forestry section is also significant, estimated to be more than 775 million euros ([Silveira, 2026](#)). The Fisheries industry was also adversely impacted, with estimated vessel losses equal to or exceeding 30% of sales volume at national fish markets between November 2025 and January 2026, compared to the same months of the previous year ([TSE, 2026](#)). The losses in the poultry industry have been estimated at 30 million euros, with an expected 5% drop in egg production ([Mar. 2026](#)).

Northern **Morocco**, especially the Tanger-Tétouan-Al Hoceima (TTA) region, is the country's second-largest economic centre, accounting for about 10.4% of national GDP. In this region, livelihoods are primarily influenced by irrigated commercial agriculture, agro-food industry and logistics, smallholder mixed farming and livestock, artisanal and industrial fisheries, coastal tourism, and urban services and manufacturing. This region also hosts one of the country's prominent manufacturing hubs, including automotive, textiles, and the agro-industry ([Fanchaouy, 2025](#)). The storm and floods have submerged 110,000 hectares of farmland, leading to substantial agricultural losses in the region and forcing the allocation of \$330 million to upgrade infrastructure and assist residents, farmers, and businesses affected in the northwestern plains of Morocco ([Eljechtimi, 2026](#)). The storm and flood events have damaged 700 small businesses, primarily micro-retail and services in old dense districts ([IFRC, 2025](#)). Transportation infrastructures have been extensively damaged, which can adversely impact the businesses in the region, such as tourism revenue loss, impacts on the productivity at the processing plants ([IFRC, 2025](#); [Agharroud, 2023](#)).

4.4 Spatial planning, critical systems, and exposure

Across northern and southern Portugal, southwestern Spain and northern Morocco, the storms translated into severe impacts because high exposure is locked into coastal and riverine areas that tend to be densely populated, and have critical infrastructure and built environment assets ([Ferreira et al. 2021](#)). Tourism activities along the coast and, consequently, tourism-driven expansion of buildings, roads, and services into former dune fields and lowlands are putting tourists in high-occupancy areas such as beaches and campsites at risk during storm events. ([Barros et al. 2022](#); [Martínez-Graña, 2016](#); [Lemos et al. 2024](#)). In many locations, there is “no room for water” as urban construction (car parks, roundabouts, shopping centers) have impermeabilized the ground significantly increasing the flood risk ([Euronews, 2026](#)).

Urban and peri-urban populations in the affected regions are concentrated along riverine areas e.g. Mondego, Tejo and tributaries in Portugal and low-lying Atlantic plains along with many historic districts and newer housing estates laying either directly in floodplains or on poorly drained terrains ([Tavares et al., 2021](#)). Floods in coastal cities also pose severe risks to ecosystems and water quality as a result of release of contaminants from poorly planned infrastructure and untreated wastewater overflow ([Laino et al., 2025](#)).

In **Spain**, in the heavily impacted region of Andalusia, floods destroyed bridges, blocked roads, and disrupted drinking water supply in several towns, leaving some communities temporarily without safe water. According to one local news source, in some houses in Cadiz, Grazalema the water has come up through the floor and flown through electrical sockets into the houses ([Water News Europe, 2026](#)). In Catalonia region, authorities closed schools, suspended sporting events and restricted non-essential

healthcare services as wind gusts of over 105km/h felled trees, disrupting road and rail traffic across the region ([RTE News, 2026](#)).

In **Portugal**, strong winds caused heavy damage in the district of Leiria where the plastic and metal industry is concentrated. The damage include the partial destruction of the municipal sports center in Leiria, damage to F-16 jets at the Monte Real air base near Leiria, and widespread reports of damage to large roofed buildings such as churches, factories, and schools across the area ([Cotality, 2026](#)). In the metropolitan area of Lisbon, high precipitation caused localized flooding and nearby Setúbal districts, particularly in low-lying areas and natural drainage basins where streets quickly filled during intense bursts. Lisbon is also affected by the burst of one of the upstream levees on the River Mondego near the medieval city of Coimbra sustaining the A1 highway that connects the cities of Lisbon and Porto ([Reuters, 2026](#)). Extensive damage to houses and roads is attributed to unplanned urban expansion combined with an unaffordable property market that lead to poor quality construction of houses with “quick and fragile solutions such as ‘self-building’” ([Euronews, 2026](#)).

The cities and infrastructure in **Morocco**, particularly in the Safi Province was heavily impacted with the most severe impacts in Medina city, particularly the Bab Chaaba and Sidi Boudheb neighbourhoods. Similarly, in Ksar El Kebir, major disruptions to transport, electricity, water supply, and education systems are reported. These areas are characterized by very high urban density (up to 400 residents per hectare), older housing stock, and structural vulnerabilities ([Reliefweb, 2026](#)). The city of Ksar El Kébir has been established on an alluvial plain, in direct contact with the Loukkos River, a land which is naturally exposed to flooding. According to the local resources ([Yabiladi, 2026](#)), by February 10, the Oued El Makhazine Dam had reached over 166% capacity prompting massive preventive evacuations and controlled releases of water which resulted in increased flooding downstream, especially where the Loukkos and Sebou rivers converge. These examples in the Mediterranean region indicate an urban expansion trend in areas at risk of flooding. This is mainly a result of inadequate conversion of peripheral and agricultural land to urban areas under demographic pressure, or extensions prompted by the tourist appeal of seaside municipalities ([El Kouiffi et al., 2025](#)).

4.5 Storm Risk Management

4.5.1 Governance, Policies, and Plans

Despite recent developments in strengthening disaster management systems, all countries experienced significant challenges in responding to the impacts of storm and floods of this scale. The challenges highlight the need for deepening coordination and alignment between national and local disaster management authorities, expanding non-structural and nature-based solutions into infrastructure and urban planning.

Spain's flood management system is highly decentralised, where primary responsibility for civil protection lies with regional and municipal authorities unless a national emergency is declared. Central oversight during major emergencies is led by the General Directorate of Civil Protection and Emergencies under the Ministry of the Interior. In recent years, Spain has reinforced its flood resilience approach through significant financial commitments. A €7 billion emergency aid package was approved to support affected populations following severe storms in Extremadura and Andalusia

([Reuters, 2026](#)). Medium-term resilience investments—including €335 million and €530 million programmes—have prioritised the renovation of hydraulic infrastructure, improved flood risk mapping, re-naturalisation of riverbeds, and restoration of riverbanks ([Smartwater, 2026](#)). These measures signal a strategic shift toward integrating nature-based solutions and risk assessments into flood management policy. Additionally, the introduction of paid climate leave for workers during extreme weather events represents an innovative integration of social protection within disaster risk governance ([Guardian, 2024](#)). Despite this robust legislative and financial framework, enforcement of land-use planning regulations has been inconsistent, and significant residential development occurred in high-risk flood zones, including encroachment onto natural floodplains ([Waternews Europe, 2025](#)).

Portugal's flood management system also operates within a decentralised civil protection framework that integrates national coordination with strong regional and municipal operational responsibilities. Strategic oversight is led by Autoridade Nacional de Emergência e Proteção Civil (ANEPC), which coordinates policy, planning, and nationwide emergency response. This includes ensuring operational coherence between northern districts and the Algarve in the south ([ANEPC, 2022](#)). Flood risk governance is further strengthened through the Agência Portuguesa do Ambiente, responsible for river basin management, flood hazard mapping, water resource regulation, and coastal erosion risk management ([Waterhub, 2026](#)). Along the coastline, the Autoridade Marítima Nacional oversees risks associated with coastal storms and high seas ([AMN, 2026](#)).

The Portuguese government has approved substantial emergency aid packages to provide immediate relief to affected households and small businesses, including grants of up to €30,000 for home repairs ([Guardian, 2026](#)). However, recent extreme storms have exposed structural vulnerabilities. Reports highlight instances of lack of sufficient urban planning, and an over-reliance on hard engineering infrastructure. Such practices have, in some cases, amplified runoff and increased exposure to flood risk ([Guardian, 2026](#)).

In **Morocco**, after the severe floods in the Gharb plain in 1995, which threatened national food security and highlighted systemic vulnerabilities ([IFRC, 1997](#)) the government introduced the National Flood Protection Plan in 2002. Adoption of Water Law in 2016 formalised a proactive flood risk management approach, integrating prevention, planning, and risk mapping into national water governance ([Loudyi et al., 2022](#)). The National Disaster Risk Management Strategy positions disaster risk management as a national priority and promotes institutional coordination across sectors and administrative levels ([World Bank Group, 2024](#)). The Fund of Solidarity against Catastrophic Events provides compensation to people impacted by disaster, while the Fund for the Fight against Natural Catastrophes finances risk reduction and resilience projects ([World Bank Group, 2024](#)). Morocco's integrated disaster risk management reform programme focuses on institutional strengthening, capacity building, and systematic coordination among central ministries, national agencies, and provincial and local authorities ([World Bank, 2024](#)). By 2019, the country had developed 145 large dams, numerous hydraulic transfer structures, and over 100 smaller dams and reservoirs, many of which serve dual purposes of water supply and flood control ([Loudyi et al., 2022](#)). Overall, Morocco's flood management system reflects a consolidated legal framework, basin-level technical planning capacity, ministerial oversight, and increasing integration of disaster risk financing mechanisms.

4.5.2 Early warning systems

Portugal, Spain, and Morocco have developed early warning systems for storms. In **Spain**, the national meteorological agency, Agencia Estatal de Meteorologia (AEmet), issues impact-based warnings for rain, wind, storm surge, and flooding, and names Atlantic storms impacting the Iberian Peninsula ([Portillo, n.d.](#)). Since 2023, ES-alerts - a national cell-broadcast system - pushes urgent alerts directly to mobile phones, allowing regional authorities to provide tailored instructions during high-level events ([Proteccion Civil, 2022](#)).

Portugal's Institute for Sea and Atmosphere similarly issues impact-based warnings ([IPMA, n.d.](#)), supported by the National Emergency and Civil Protection Authority, which manages the National System for Risk Monitoring and Communication, Special Alert, and Public Warning to ensure clear information flow between technical services and authorities ([European Civil Protection and Humanitarian Aid Operations, n.d.](#)).

In **Morocco**, the General Directorate of Meteorology operates a national EWS for extreme weather, complemented by the INDAR system, which is a flood prediction tool issuing automated alerts with up to 48 hours of lead time for flood events, including storm-related ([al Makhfi, 2019](#)). Morocco recently joined the Early Warning for All (EW4A) initiative launched by the United Nations Secretary General in 2022 to ensure all people are covered by effective early warning systems ([Kingdom of Morocco, 2025](#)). The four co-leading organizations are WMO, UNDRR, IFRC and ITU ([UN, n.d.](#)).

Across all three countries, authorities issued early warnings which enabled timely anticipatory actions, helping limit impacts and keep fatalities low. This included evacuating at least 108,000 people in Morocco ([Eljehtimi, 2026](#)), 3,000 in Portugal ([Pereira, 2026](#)), and 11,000 in Spain ([Nazca & Pereira, 2026](#)).

5 Summary of findings

Although substantial uncertainties remain across observational records, model simulations, and regional datasets and quantitative estimates vary depending on methodological choices and spatial coverage, all the available lines of evidence collectively indicate an increase in the intensity of the most extreme heavy precipitation events. The influence of anthropogenic warming on heavy rainfall exhibits clear regional differences, with particularly robust evidence for intensification in the northern region. However, the absence of similarly strong or consistent signals in the southern region should not be interpreted as evidence of no effect; rather, it reflects limitations in data availability and high localised variability.

While many countries have made measurable progress in strengthening disaster risk management frameworks, significant gaps persist in the alignment of national and municipal early warning systems, as well as in local-level response capacity and preparedness. In light of increasing exposure, persistent uncertainties, and the increasingly more severe occurrences of extreme rainfall, precautionary spatial planning, in particular the avoidance of new development in floodplains remains an urgent and effective risk reduction strategy.

Data availability

All time series used in the attribution analysis are available via the Climate Explorer.

Acknowledgements

Data used in this study were obtained from and preprocessed using JASMIN, the UK's collaborative data analysis environment (<https://www.jasmin.ac.uk>); the KNMI Climate explorer web tool (<https://climexp.knmi.nl/start.cgi>); and resources of the Deutsches Klimarechenzentrum (DKRZ), granted by its Scientific Steering Committee (WLA) under project ID bk1088, including datasets provided by ESGF via the DKRZ data pool.

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References

All references are given as hyperlinks in the text.

Appendices

A1 Data and methods

A1.1 Observational data

We first use observational and reanalysis data to estimate the return period of a similar event in the present day and to assess the historical trends in extreme rainfall associated with both increasing GMST and with the changing NAO state. The datasets used are as follows:

E-OBS - This is a gridded land-only observation dataset, formed from the interpolation of station-derived meteorological observations over Europe ([Cornes et al., 2018](#)). We use gridded precipitation from version 32.0e of this dataset, at a spatial resolution of $0.25^\circ \times 0.25^\circ$, from 1920 to the end of January 2026.

ERA5 - The European Centre for Medium-Range Weather Forecasts's 5th generation reanalysis product, ERA5, is a gridded dataset that combines historical observations into global estimates using advanced modelling and data assimilation systems ([Hersbach et al., 2020](#)). We use daily precipitation data from this product at a resolution of $0.25^\circ \times 0.25^\circ$. We use reanalysis data until the end of January 2026, extended with analysis data for February to cover the period of the event. Data used in the main analysis was obtained from [KNMI's Climate Explorer](#) tool.

CPC - This is the gridded product from [NOAA](#) PSL, Boulder, Colorado, USA, known as the CPC Global Unified Daily Gridded data, available at $0.5^\circ \times 0.5^\circ$ resolution, for the period 1979 - present. We use daily precipitation data.

MSWEP - The Multi-Source Weighted-Ensemble Precipitation v2.8 dataset (updated from [Beck et al., 2019](#)) is fully global, available at 3-hourly intervals and at 0.1° spatial resolution, available from 1979 to ~3 hours from real-time. This product combines gauge-, satellite-, and reanalysis-based data, including ERA5.

CHIRPS - The rainfall product developed by the UC Santa Barbara Climate Hazards Group called "Climate Hazards Group InfraRed Precipitation with Station data" (CHIRPS; [Funk et al. 2015](#)). Daily data are available at 0.05° resolution, from 1981 to the end of January 2026. The product incorporates satellite imagery with in-situ station data.

GHCNd - The Global Historical Climatology Network daily ([GHCNd](#)) is a global dataset of daily meteorological observations from more than 100,000 land-based weather stations in 180 countries and territories. The data quality varies by station and cover intervals ranging from less than a year to more than 175 years.

Covariates

As a measure of anthropogenic climate change we use the (low-pass filtered) global mean surface temperature (GMST), where GMST is taken from the National Aeronautics and Space Administration

(NASA) Goddard Institute for Space Science (GISS) surface temperature analysis (GISTEMP, [Hansen et al., 2010](#) and [Lenssen et al. 2019](#)). To remove the short-term influence of the El Niño - Southern Oscillation on global mean temperatures, we use a four-year running mean of the GMST, centred on the third year.

The observed North Atlantic Oscillation (NAO) index is computed as the difference in monthly ERA5 Mean Sea Level Pressure (MSLP) between two boxes located around Iceland (25W-16W, 63N-70N) and the Azores (28W-20W, 36N-40N) consistent with [Dunstone et al. \(2016\)](#). The monthly series is averaged over December-February each year (labelled in February) and normalised to have mean zero and standard deviation one over the period from 1990-2020. Because ERA5 reanalysis was used, this time series is only available from 1950 onwards.

A1.2 Model and experiment descriptions

We use 2 ensembles of climate models from climate modelling experiments using different framings ([Philip et al., 2020](#)): regional climate models and high resolution Sea Surface Temperature (SST) driven global circulation models (GCMs).

1. Euro-CORDEX

Coordinated Regional Climate Downscaling Experiment (CORDEX) for the European Domain at 0.11° resolution (EUR-11, [Jacob et al., 2014](#); [Vautard et al., 2021](#)). The ensemble consists of 75 runs from combinations of fourteen regional climate models (RCMs) with boundary conditions from eight GCMs from the CMIP5 ensemble (see Tables A.3.1 and A.3.2 for details). These simulations are composed of historical simulations from 1950 or 1970 up to 2005, and extended to the year 2100 using the RCP8.5 scenario.

Smoothed GMST time series are computed as the area-weighted mean of the surface air temperatures in the parent GCM, while the NAO series is computed from the MSLP fields in the parent GCM, using the same procedure as for observations. MSLP fields were not available at the time of writing for three GCM variants, reducing the total number of runs available to 61.

2. HighResMIP

The High Resolution Model Intercomparison Project — SST-forced model ensemble ([Haarsma et al. 2016](#)), the simulations for which span from 1950 to 2050. The SST and sea ice forcings for the period 1950-2014 are obtained from the 0.25° x 0.25° Hadley Centre Global Sea Ice and Sea Surface Temperature dataset that have undergone area-weighted regridding to match the climate model resolution. For the ‘future’ time period (2015-2050), SST/sea-ice data are derived from RCP8.5 (CMIP5) data, and combined with greenhouse gas forcings from SSP5-8.5 (CMIP6) simulations (see Section 3.3 of Haarsma et al. 2016 for further details).

A1.3 Statistical methods

Methods for observational and model analysis and for model evaluation and synthesis are used according to the World Weather Attribution Protocol, described in [Philip et al., \(2020\)](#), with supporting details found in [van Oldenborgh et al., \(2021\)](#), [Ciavarella et al., \(2021\)](#), [Otto et al., \(2024\)](#) and [here](#). The key steps, presented in sections 3-6, are: (3) trend estimation from observations; (4) model validation; (5) multi-method multi-model attribution; and (6) synthesis of the attribution statement. In this report we analyse time series of Rx1day-ONDJFM (see Section 1.3).

A nonstationary Generalised Extreme Value (GEV) distribution is used to model Rx1day-ONDJFM in both regions. The distribution is assumed to scale exponentially with the covariates, with the dispersion (the ratio between the standard deviation and the mean) remaining constant over time. The parameters of the statistical model are estimated using maximum likelihood.

For each time series we calculate the return period and intensity of the event under study for the 2026GMST and for 1.3°C cooler GMST: this allows us to compare the climate of now and of the preindustrial past (1850-1900, based on the [Global Warming Index](#)), by calculating the probability ratio (PR; the factor-change in the event's probability) and change in intensity of the event.

In order to examine the effect of the NAO state on Rx1day-ONDJFM alongside that of increasing GMST, we extend the nonstationary model to accommodate an additional covariate. All results quoted are from a statistical model including both covariates.

The variable of interest, X , is assumed to follow a GEV distribution in which the location and scale parameters vary with both GMST and the NAO:

$$X \sim GEV(\mu, \sigma, \xi \mid \mu_0, \sigma_0, \alpha, \beta, T, I),$$

where X denotes the variable of interest, rainy-season precipitation; T is the smoothed GMST; I is the normalised NAO index; μ_0 , σ_0 and ξ are the location, scale and shape parameters of the nonstationary distribution; and α , β are the trends due to GMST and NAO, respectively. As a result, the location and scale of the distribution have a different value in each year, determined by both the GMST and NAO states. Maximum likelihood estimation is used to estimate the model parameters, with

$$\mu = \mu_0 \exp\left(\frac{\alpha T + \beta I}{\mu_0}\right) \quad \text{and} \quad \sigma = \sigma_0 \exp\left(\frac{\alpha T + \beta I}{\mu_0}\right).$$

This formulation reflects the Clausius Clapeyron relation, which implies that precipitation scales exponentially with temperature ([Trenberth et al., 2003](#), [O’Gorman and Schneider 2009](#)), and so that precipitation will scale exponentially with GMST. Under this model, the effects of GMST and the NAO index are assumed to be independent of one another, so that the change in intensity due to GMST is unaffected by the change in intensity due to the NAO phase. We note that this may not be the case in the real world, but do not expect the qualitative findings of this study to be affected by this simplifying assumption.

A1.4 Circulation analogues

Atmospheric flow analogues can be used to assess changes in the intensity of dynamically similar events or changes in the frequency of occurrence of particular circulation patterns ([Vautard et al., 2023](#); [Jézéquel et al., 2018](#), [Thompson et al 2024](#)). Here, we use ERA5 data to assess analogues identified from mean sea level pressure (SLP), to detect changes in the frequency of circulation patterns similar to those associated with the heavy rainfall event and in the weather characteristics associated with similar weather patterns.

To identify the most similar events, we compute the Euclidean distance between the SLP anomaly field of the 4th February 2026 and every other day (1950–2023) over the region bounded by [35°E to 20°E, 40° to 60°N]. To avoid double-counting persistent events, the identified events must be separated by at least 5 days. The region and circulation variable were determined by assessing the event itself, and earlier current understanding of the circulation drivers of similar events ([Holgate et al 2023](#)).

To detect trends in the circulation pattern and intensity since 1950 we identify the closest 29 analogues across each period (1950-1979 and 1994-2023) from January to March (JFM). This corresponds to the closest 1% of days in each period, one month either side of the event. The average weather conditions associated with the two sets of analogues - called ‘composites’ - are then compared to assess differences between the two periods. We also assess the change in frequency of the closest analogues through time. This is assessed at three different thresholds - the upper 5% of days, upper 10%, and upper 20%. Differences in modes of internal variability between the two time periods can also induce differences in the weather conditions, therefore we cannot identify the role of climate change solely by comparing analogue sets in reanalyses.

A2 Supporting tables & figures

A2.1 Additional results for sections 2.1-2.2

Dataset	Event magnitude (mm)	Return period	Change in intensity		Probability ratio	
			GMST	NAO	GMST	NAO
ERA5 (1950-) GMST + NAO	40.4	39.8 (8.99, Inf)	23 (-0.26, 47.7)	5.36 (0.66, 9.58)	64.9 (0.98, Inf)	2.1 (1.15, 29.2)
E-Obs (1950-) GMST + NAO	50.8*	40*	49.2 (23.6, 77.3)	4.44 (-1.13, 9.33)	48.4* (2.62, Inf)	1.42* (0.929, 4.57)
ERA5 (1950-) GMST	40.4	82.6 (13.2, Inf)	17.7 (-4.36, 43.4)	-	52.8 (0.364, Inf)	-
E-Obs (1950-) GMST	48.3*	40*	42.4 (17.8, 65.6)	-	29.5* (2.16, Inf)	-
E-Obs (1920-) GMST	46.5*	40*	38.2 (20.8, 54.8)	-	26.3* (3.11, 189000)	-

Table A2.1: Estimated return period (where available), change in intensity and change in likelihood (probability ratio) of the observed maximum rainfall in the southern region in ERA5 and E-Obs. Top two rows show the full model fitted to all years from 1950-2026. Top two rows are as in Table 2.1 for reference; bottom three rows (grey text) show the partial model in which Rx1day depends on GMST only, for all data from 1950-2026 for ERA5 and E-Obs and for the full E-Obs time series from 1920-2026. For E-Obs, which does have coverage of the February 4th storm at the time of writing, a hypothetical 40-year event was used to estimate the expected event magnitude and the probability ratio (marked with *).

Dataset	Event magnitude (mm)	Return period	Change in intensity		Probability ratio	
			GMST	NAO	GMST	NAO
ERA5 (1950-) GMST + NAO	52	3.22 (1.56, 9.35)	19.1 (-1.01, 47.3)	1.61 (-1.75, 5.29)	3.45 (0.925, Inf)	1.09 (0.888, 1.36)
E-Obs (1950-) GMST + NAO	45.4	1.96 (1.29, 4.05)	39.3 (16.4, 70.5)	2.66 (-1.04, 6.67)	7.12 (2.71, 46.9)	1.1 (0.958, 1.35)
ERA5 (1950-) GMST	52	3.58 (1.81, 10.4)	17 (-1.68, 40.5)	-	3.18 (0.885, 407)	-
E-Obs (1950-) GMST	45.4	2.21 (1.43, 4.78)	35.4 (12.4, 61.6)	-	6.56 (2.24, 39.6)	-
E-Obs (1920-) GMST	45.4	1.93 (1.35, 3.48)	43.3 (22.1, 68.1)	-	8.86 (3.88, 24)	-

Table A2.2: Estimated return period (where available), change in intensity and change in likelihood (probability ratio) of the observed maximum rainfall in the northern region in ERA5 and E-Obs. Top two rows show the full model fitted to all years from 1950-2026. Top two rows are as in Table 2.2 for reference; bottom three rows (grey text) show the partial model in which Rx1day depends on GMST only, for all data from 1950-2026 for ERA5 and E-Obs and for the full E-Obs time series from 1920-2026, for comparison.

A2.2 Additional figures for Section 2.3

PR and SLP ERA5 past analogues JFM 1950-1979

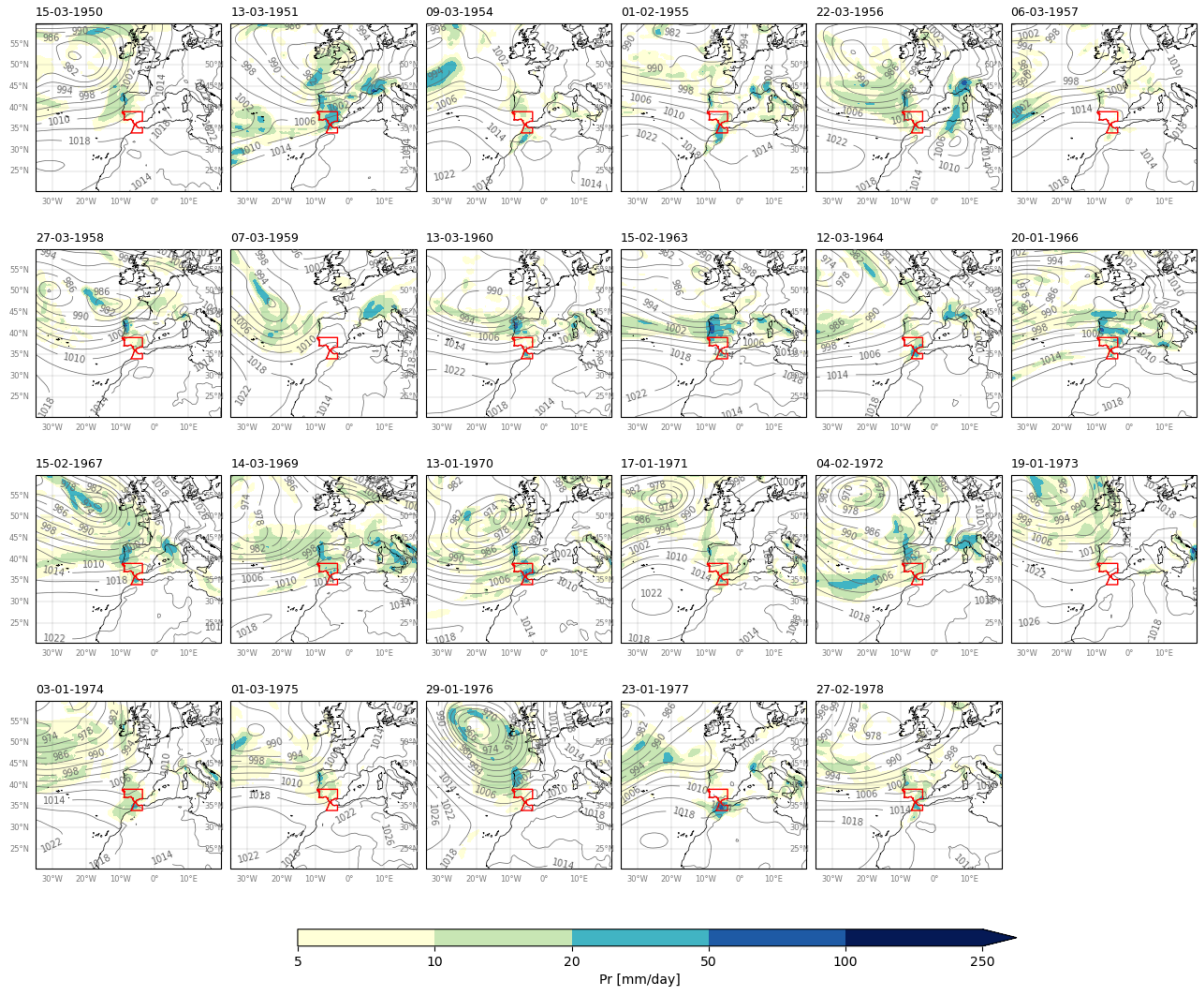


Figure A2.1: Rainfall and SLP for each of the analogues found over the period of 1950-1979.

PR and SLP ERA5 present analogues JFM 1994-2023

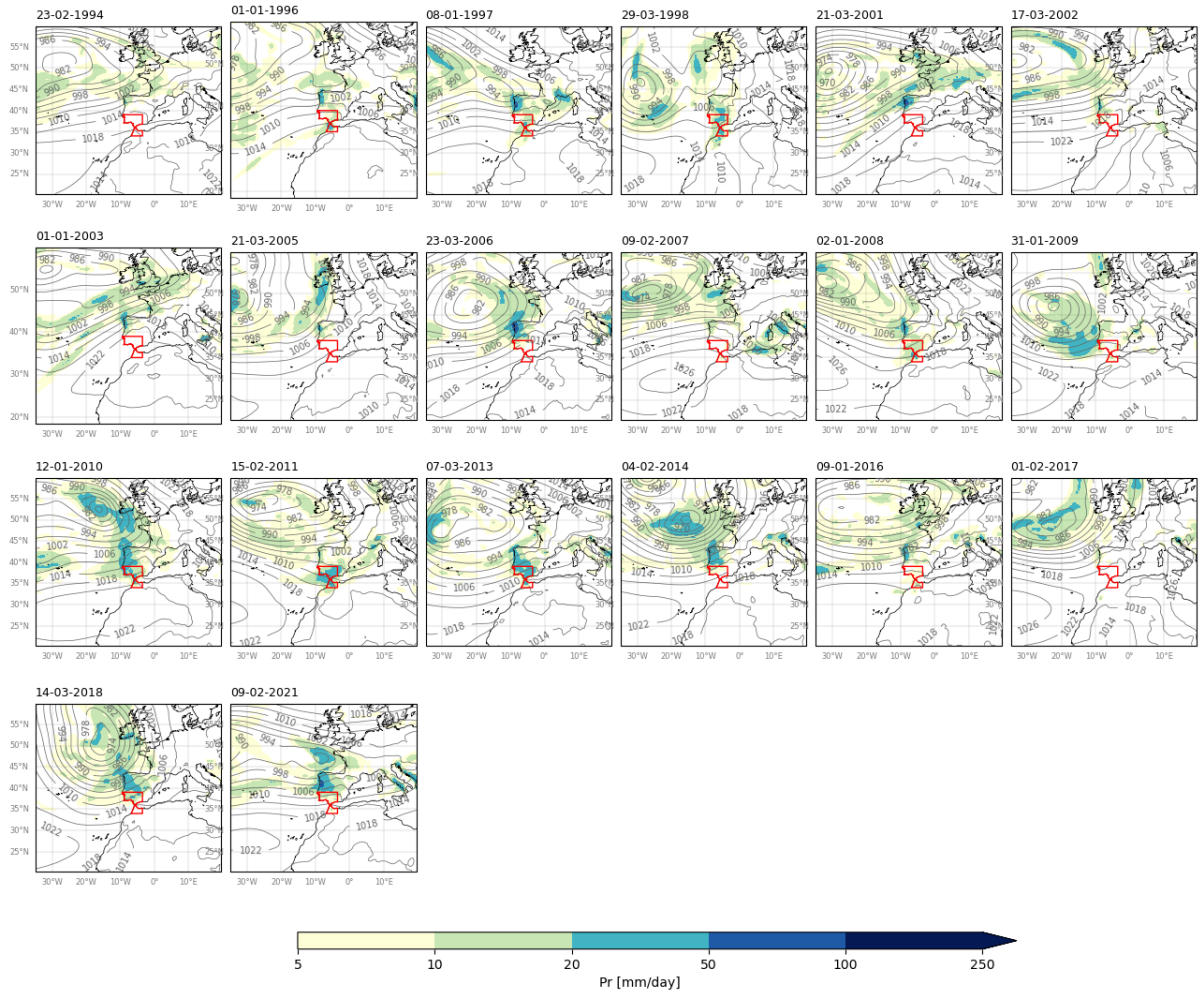


Figure A2.2: Rainfall and SLP for each of the analogues found over the period of 1995-2023

A2.3 Synthesis of probability ratios

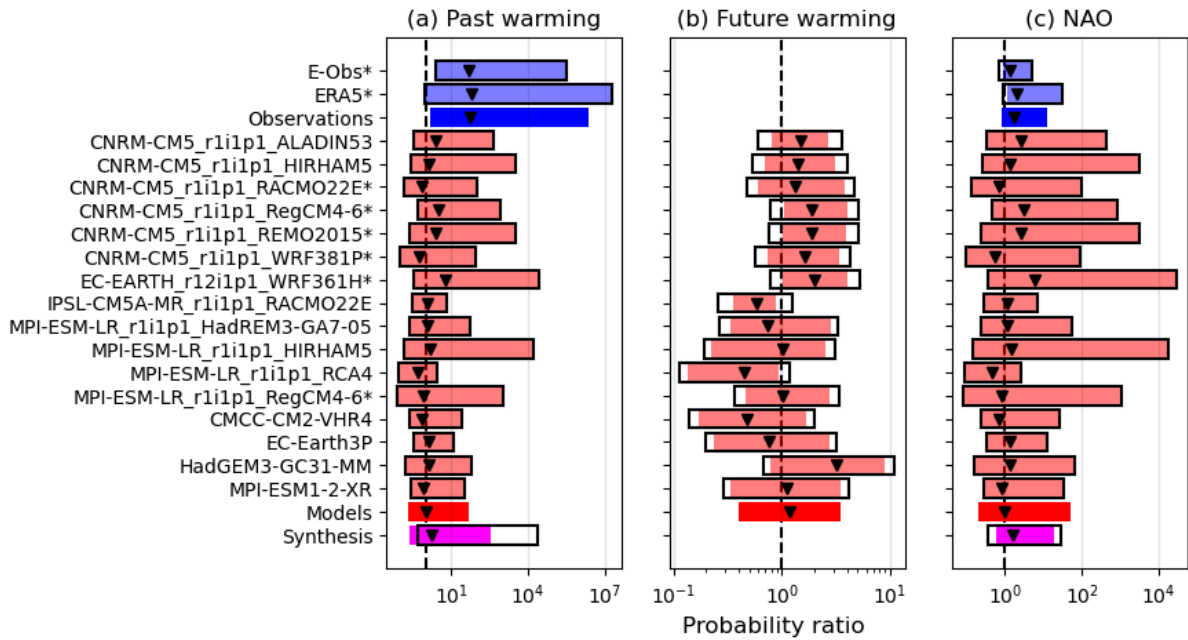


Figure A2.3: Synthesis of change in likelihood of observing what is currently a one-in-40-year $Rx1day$ -ONDJFM event in the southern region when comparing (a) the 2026 climate and a 1.3°C cooler climate representing the preindustrial past; (b) the 2026 climate and a 1.3°C warmer climate; (c) the 2026 NAO state and a neutral NAO state. Datasets in which the bootstrapped upper bound was infinite are marked with *. For these datasets a finite upper bound was inferred using the approach described in [Otto et al. \(2024\)](#)

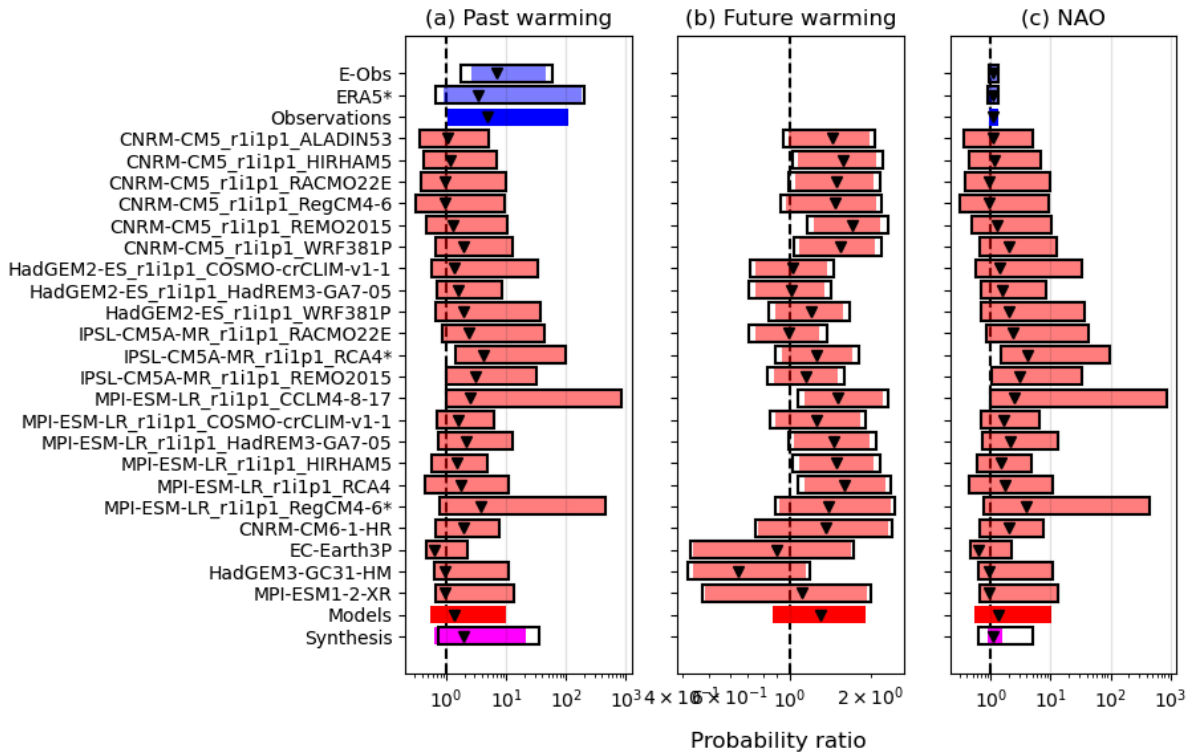


Figure A2.4: As Figure A2.3, but for the northern region.

A3. Model evaluation tables

Table A3.1: Evaluation results for Rx1day-ONDJFM in the southern study region. The evaluations of the seasonal cycle and spatial pattern are shown, along with the estimated dispersion and shape parameters, including 95% confidence intervals obtained by bootstrapping. The final evaluation is based on all five criteria.

Obs / models	Seasonal	Spatial	Dispersion	Shape.parameter	Overall	Keep
E-Obs			0.223 (0.154, 0.262)	0.00664 (-0.196, 0.351)		
ERA5			0.226 (0.179, 0.259)	-0.165 (-0.369, 0.0418)		
CanESM2_rli1p1 CCLM4-8-17	reasonable	reasonable	0.312 (0.223, 0.371)	-0.068 (-0.436, 0.232)	reasonable	N
CanESM2_rli1p1 REMO2015	good	good	0.271 (0.207, 0.326)	0.0154 (-0.415, 0.379)	reasonable	N
CNRM-CM5_rli1p1 ALADIN53	good	good	0.226 (0.154, 0.277)	0.0845 (-0.216, 0.403)	good	Y
CNRM-CM5_rli1p1 ALADIN63	bad	good	0.182 (0.128, 0.22)	-0.0648 (-0.534, 0.275)	bad	N
CNRM-CM5_rli1p1 ALARO-0	reasonable	good	0.234 (0.172, 0.281)	-0.0497 (-0.368, 0.178)	reasonable	N
CNRM-CM5_rli1p1 CCLM4-8-17	good	reasonable	0.216 (0.14, 0.258)	-0.0422 (-0.331, 0.301)	reasonable	N
CNRM-CM5_rli1p1 COSMO-crCLIM-v1-1	reasonable	good	0.239 (0.168, 0.293)	0.0735 (-0.214, 0.419)	reasonable	N
CNRM-CM5_rli1p1 HadREM3-GA7-05	reasonable	good	0.262 (0.199, 0.308)	-0.123 (-0.457, 0.206)	reasonable	N
CNRM-CM5_rli1p1 HIRHAM5	good	good	0.243 (0.176, 0.3)	0.088 (-0.332, 0.394)	good	Y
CNRM-CM5_rli1p1 RACMO22E	good	good	0.195 (0.138, 0.242)	-0.0499 (-0.52, 0.443)	good	Y
CNRM-CM5_rli1p1 RCA4	reasonable	good	0.216 (0.148, 0.26)	-0.262 (-0.673, 0.1)	reasonable	N
CNRM-CM5_rli1p1 RegCM4-6	good	good	0.213 (0.128, 0.248)	-0.00612 (-0.387, 0.603)	good	Y
CNRM-CM5_rli1p1 REMO2015	good	good	0.257 (0.187, 0.305)	-0.133 (-0.4, 0.127)	good	Y
CNRM-CM5_rli1p1 WRF381P	good	good	0.198 (0.138, 0.231)	0.0291 (-0.16, 0.329)	good	Y
EC-EARTH_r12i1p1 CCLM4-8-17	reasonable	good	0.257 (0.189, 0.299)	-0.135 (-0.436, 0.0788)	reasonable	N
EC-EARTH_r12i1p1 COSMO-crCLIM-v1-1	reasonable	good	0.286 (0.216, 0.338)	-0.119 (-0.715, 0.189)	reasonable	N
EC-EARTH_r12i1p1 HadREM3-GA7-05	good	good	0.274 (0.209, 0.32)	-0.175 (-0.515, 0.105)	reasonable	N
EC-EARTH_r12i1p1 HIRHAM5	reasonable	reasonable	0.235 (0.176, 0.272)	-0.192 (-0.624, -0.0125)	reasonable	N

EC-EARTH_r12i1p1 RACMO22E	good	reasonable	0.196 (0.146, 0.231)	-0.152 (-0.429, 0.0626)	reasonable	N
EC-EARTH_r12i1p1 RCA4	reasonable	good	0.242 (0.172, 0.286)	-0.283 (-0.743, 0.184)	reasonable	N
EC-EARTH_r12i1p1 RegCM4-6	reasonable	good	0.201 (0.144, 0.236)	-0.141 (-0.383, 0.206)	reasonable	N
EC-EARTH_r12i1p1 REMO2015	good	reasonable	0.189 (0.139, 0.222)	-0.0601 (-0.462, 0.174)	reasonable	N
EC-EARTH_r12i1p1 WRF361H	good	good	0.212 (0.158, 0.251)	0.0231 (-0.289, 0.321)	good	Y
EC-EARTH_r12i1p1 WRF381P	reasonable	good	0.256 (0.185, 0.316)	0.0353 (-0.472, 0.372)	reasonable	N
HadGEM2-ES_r1i1p1 ALADIN63	reasonable	good	0.257 (0.194, 0.306)	-0.4 (-0.843, -0.102)	bad	N
HadGEM2-ES_r1i1p1 CCLM4-8-17	reasonable	good	0.328 (0.242, 0.38)	-0.302 (-0.695, 0.0712)	reasonable	N
HadGEM2-ES_r1i1p1 COSMO-crCLIM-v1-1	good	good	0.342 (0.259, 0.396)	-0.381 (-0.816, -0.0216)	bad	N
HadGEM2-ES_r1i1p1 HadREM3-GA7-05	good	good	0.327 (0.248, 0.381)	-0.248 (-0.715, 0.0753)	reasonable	N
HadGEM2-ES_r1i1p1 HIRHAM5	reasonable	good	0.309 (0.225, 0.354)	-0.264 (-0.693, 0.239)	reasonable	N
HadGEM2-ES_r1i1p1 RACMO22E	reasonable	good	0.295 (0.214, 0.343)	-0.152 (-0.704, 0.394)	reasonable	N
HadGEM2-ES_r1i1p1 RCA4	reasonable	reasonable	0.32 (0.246, 0.372)	-0.154 (-0.577, 0.141)	reasonable	N
HadGEM2-ES_r1i1p1 RegCM4-6	good	reasonable	0.243 (0.161, 0.295)	-0.208 (-0.618, 0.0477)	reasonable	N
HadGEM2-ES_r1i1p1 REMO2015	good	good	0.325 (0.24, 0.378)	-0.241 (-0.703, -0.0279)	reasonable	N
HadGEM2-ES_r1i1p1 WRF361H	good	good	0.318 (0.238, 0.378)	-0.521 (-0.81, -0.193)	bad	N
HadGEM2-ES_r1i1p1 WRF381P	good	good	0.285 (0.2, 0.332)	-0.0984 (-0.313, 0.234)	reasonable	N
IPSL-CM5A-MR_r1i1p1 HIRHAM5	reasonable	good	0.241 (0.172, 0.282)	0.0699 (-0.446, 0.471)	reasonable	N
IPSL-CM5A-MR_r1i1p1 RACMO22E	good	good	0.254 (0.175, 0.292)	0.0853 (-0.371, 0.479)	good	Y
IPSL-CM5A-MR_r1i1p1 RCA4	good	good	0.304 (0.176, 0.357)	0.213 (-0.198, 1.12)	reasonable	N
IPSL-CM5A-MR_r1i1p1 REMO2015	good	good	0.243 (0.162, 0.283)	0.196 (-0.31, 0.76)	reasonable	N
IPSL-CM5A-MR_r1i1p1 WRF381P	reasonable	good	0.262 (0.129, 0.312)	0.0605 (-0.286, 1.01)	reasonable	N
MIROC5_r1i1p1 CCLM4-8-17	reasonable	good	0.19 (0.131, 0.222)	-0.0903 (-0.317, 0.227)	reasonable	N
MIROC5_r1i1p1 REMO2015	reasonable	reasonable	0.167 (0.104, 0.2)	0.166 (-0.304, 0.997)	reasonable	N
MIROC5_r1i1p1 WRF361H	reasonable	good	0.216 (0.137, 0.265)	-0.0438 (-0.334, 0.378)	reasonable	N

MPI-ESM-LR_rli1p1 ALADIN63	bad	good	0.176 (0.127, 0.227)	-0.067 (-0.602, 0.307)	bad	N
MPI-ESM-LR_rli1p1 CCLM4-8-17	good	good	0.229 (0.168, 0.278)	-0.47 (-0.789, -0.181)	bad	N
MPI-ESM-LR_rli1p1 COSMO-crCLIM-v1-1	good	good	0.218 (0.156, 0.267)	-0.407 (-0.768, -0.103)	bad	N
MPI-ESM-LR_rli1p1 HadREM3-GA7-05	good	good	0.202 (0.132, 0.253)	-0.366 (-0.743, -0.0925)	good	Y
MPI-ESM-LR_rli1p1 HIRHAM5	good	good	0.197 (0.142, 0.24)	-0.326 (-0.765, -0.124)	good	Y
MPI-ESM-LR_rli1p1 RACMO22E	bad	good	0.204 (0.141, 0.247)	-0.464 (-0.789, -0.0368)	bad	N
MPI-ESM-LR_rli1p1 RCA4	good	good	0.2 (0.148, 0.237)	-0.0669 (-0.522, 0.266)	good	Y
MPI-ESM-LR_rli1p1 RegCM4-6	good	good	0.195 (0.145, 0.234)	-0.297 (-0.769, -0.0725)	good	Y
MPI-ESM-LR_rli1p1 REMO2009	bad	good	0.201 (0.15, 0.234)	-0.259 (-0.551, 0.0536)	bad	N
NorESM1-M_rli1p1 ALADIN63	reasonable	good	0.258 (0.195, 0.302)	-0.276 (-0.658, 0.027)	reasonable	N
NorESM1-M_rli1p1 COSMO-crCLIM-v1-1	reasonable	good	0.298 (0.214, 0.336)	-0.0778 (-0.5, 0.417)	reasonable	N
NorESM1-M_rli1p1 HadREM3-GA7-05	reasonable	good	0.284 (0.213, 0.32)	-0.162 (-0.504, 0.274)	reasonable	N
NorESM1-M_rli1p1 HIRHAM5	reasonable	good	0.257 (0.182, 0.302)	-0.0349 (-0.363, 0.342)	reasonable	N
NorESM1-M_rli1p1 RACMO22E	reasonable	good	0.259 (0.195, 0.297)	-0.235 (-0.515, 0.00343)	reasonable	N
NorESM1-M_rli1p1 RCA4	reasonable	good	0.281 (0.191, 0.331)	-0.343 (-0.746, 0.167)	reasonable	N
NorESM1-M_rli1p1 RegCM4-6	reasonable	good	0.231 (0.168, 0.277)	-0.192 (-0.781, 0.000763)	reasonable	N
NorESM1-M_rli1p1 REMO2015	reasonable	good	0.276 (0.21, 0.315)	-0.221 (-0.583, 0.0112)	reasonable	N
NorESM1-M_rli1p1 WRF381P	reasonable	good	0.33 (0.204, 0.395)	-0.149 (-0.349, 0.224)	reasonable	N
CMCC-CM2-HR4	bad	reasonable	0.294 (0.205, 0.359)	-0.153 (-0.476, 0.144)	bad	N
CMCC-CM2-VHR4	reasonable	reasonable	0.228 (0.175, 0.264)	0.0581 (-0.193, 0.267)	reasonable	Y
CNRM-CM6-1	bad	good	0.179 (0.135, 0.211)	-0.359 (-0.807, -0.167)	bad	N
CNRM-CM6-1-HR	bad	reasonable	0.156 (0.114, 0.188)	-0.239 (-0.666, -0.0143)	bad	N
EC-Earth3P	good	good	0.249 (0.17, 0.302)	-0.0807 (-0.31, 0.188)	good	Y
EC-Earth3P-HR	good	good	0.287 (0.183, 0.343)	-0.0841 (-0.273, 0.273)	duplicate	N
HadGEM3-GC31-HM	good	good	0.32 (0.254, 0.367)	-0.0892 (-0.477, 0.152)	duplicate	N

HadGEM3-GC31-LM	good	reasonable	0.277 (0.199, 0.332)	0.0391 (-0.627, 0.435)	duplicate	N
HadGEM3-GC31-MM	good	good	0.242 (0.169, 0.281)	0.00184 (-0.36, 0.329)	good	Y
MPI-ESM1-2-HR	good	good	0.281 (0.202, 0.332)	0.187 (-0.0508, 0.471)	duplicate	N
MPI-ESM1-2-XR	reasonable	reasonable	0.277 (0.214, 0.328)	-0.285 (-0.706, -0.117)	reasonable	Y

Table A3.2: Evaluation results for Rx1day-ONDJFM in the northern study region. The evaluations of the seasonal cycle and spatial pattern are shown, along with the estimated dispersion and shape parameters, including 95% confidence intervals obtained by bootstrapping. The final evaluation is based on all five criteria.

Obs / models	Seasonal	Spatial	Dispersion	Shape.parameter	Overall	Keep
E-Obs			0.219 (0.178, 0.248)	-0.113 (-0.308, 0.022)		
ERA5			0.227 (0.188, 0.259)	-0.184 (-0.544, -0.0479)		
CanESM2_rli1p1 CCLM4-8-17	reasonable	good	0.214 (0.156, 0.266)	-0.0616 (-0.51, 0.254)	reasonable	N
CanESM2_rli1p1 REMO2015	good	good	0.217 (0.157, 0.257)	-0.154 (-0.668, 0.131)	reasonable	N
CNRM-CM5_rli1p1 ALADIN53	good	good	0.192 (0.132, 0.231)	-0.142 (-0.551, 0.0764)	good	Y
CNRM-CM5_rli1p1 ALADIN63	bad	good	0.161 (0.118, 0.194)	-0.217 (-0.552, 0.0153)	bad	N
CNRM-CM5_rli1p1 ALARO-0	reasonable	good	0.163 (0.115, 0.189)	-0.0514 (-0.584, 0.245)	reasonable	N
CNRM-CM5_rli1p1 CCLM4-8-17	good	reasonable	0.182 (0.125, 0.215)	-0.138 (-0.528, 0.157)	reasonable	N
CNRM-CM5_rli1p1 COSMO-crCLIM-v1-1	reasonable	good	0.24 (0.171, 0.295)	-0.377 (-0.73, -0.168)	reasonable	N
CNRM-CM5_rli1p1 HadREM3-GA7-05	reasonable	good	0.21 (0.148, 0.256)	-0.368 (-0.737, -0.123)	reasonable	N
CNRM-CM5_rli1p1 HIRHAM5	good	good	0.217 (0.156, 0.258)	-0.24 (-0.58, -0.0299)	good	Y
CNRM-CM5_rli1p1 RACMO22E	good	good	0.228 (0.173, 0.267)	-0.318 (-0.662, -0.12)	good	Y
CNRM-CM5_rli1p1 RCA4	reasonable	good	0.224 (0.16, 0.255)	-0.104 (-0.583, 0.274)	reasonable	N
CNRM-CM5_rli1p1 RegCM4-6	good	good	0.21 (0.155, 0.24)	-0.203 (-0.421, 0.107)	good	Y
CNRM-CM5_rli1p1 REMO2015	good	good	0.217 (0.16, 0.256)	-0.19 (-0.502, 0.15)	good	Y
CNRM-CM5_rli1p1 WRF381P	good	good	0.22 (0.156, 0.263)	-0.112 (-0.375, 0.285)	good	Y

EC-EARTH_r12i1p1 CCLM4-8-17	reasonable	good	0.182 (0.133, 0.222)	0.0554 (-0.4, 0.415)	reasonable	N
EC-EARTH_r12i1p1 COSMO-crCLIM-v1-1	reasonable	good	0.23 (0.16, 0.275)	-0.116 (-0.538, 0.195)	reasonable	N
EC-EARTH_r12i1p1 HadREM3-GA7-05	good	good	0.175 (0.112, 0.215)	-0.0146 (-0.403, 0.441)	reasonable	N
EC-EARTH_r12i1p1 HIRHAM5	reasonable	reasonable	0.179 (0.112, 0.22)	0.0688 (-0.397, 0.526)	reasonable	N
EC-EARTH_r12i1p1 RACMO22E	good	reasonable	0.197 (0.143, 0.237)	0.0371 (-0.299, 0.316)	reasonable	N
EC-EARTH_r12i1p1 RCA4	reasonable	good	0.198 (0.102, 0.246)	0.313 (-0.0681, 1.78)	reasonable	N
EC-EARTH_r12i1p1 RegCM4-6	reasonable	good	0.231 (0.136, 0.277)	-0.0343 (-0.364, 0.649)	reasonable	N
EC-EARTH_r12i1p1 REMO2015	good	reasonable	0.205 (0.13, 0.248)	-0.0137 (-0.29, 0.37)	reasonable	N
EC-EARTH_r12i1p1 WRF361H	good	good	0.187 (0.139, 0.239)	0.0426 (-0.502, 0.338)	reasonable	N
EC-EARTH_r12i1p1 WRF381P	reasonable	good	0.261 (0.195, 0.3)	-0.00402 (-0.361, 0.29)	reasonable	N
HadGEM2-ES_r1i1p1 ALADIN63	reasonable	good	0.213 (0.133, 0.258)	-0.135 (-0.491, 0.285)	reasonable	N
HadGEM2-ES_r1i1p1 CCLM4-8-17	reasonable	good	0.264 (0.2, 0.305)	-0.101 (-0.494, 0.187)	reasonable	N
HadGEM2-ES_r1i1p1 COSMO-crCLIM-v1-1	good	good	0.252 (0.186, 0.298)	-0.0192 (-0.426, 0.252)	good	Y
HadGEM2-ES_r1i1p1 HadREM3-GA7-05	good	good	0.239 (0.179, 0.276)	-0.0412 (-0.329, 0.222)	good	Y
HadGEM2-ES_r1i1p1 HIRHAM5	reasonable	good	0.259 (0.204, 0.295)	-0.00907 (-0.425, 0.282)	reasonable	N
HadGEM2-ES_r1i1p1 RACMO22E	reasonable	good	0.273 (0.194, 0.315)	-0.0372 (-0.416, 0.25)	reasonable	N
HadGEM2-ES_r1i1p1 RCA4	reasonable	reasonable	0.293 (0.209, 0.343)	-0.0292 (-0.303, 0.255)	reasonable	N
HadGEM2-ES_r1i1p1 RegCM4-6	good	reasonable	0.293 (0.223, 0.339)	-0.0106 (-0.306, 0.31)	reasonable	N
HadGEM2-ES_r1i1p1 REMO2015	good	good	0.248 (0.154, 0.305)	0.163 (-0.27, 0.877)	reasonable	N
HadGEM2-ES_r1i1p1 WRF361H	good	good	0.21 (0.151, 0.254)	0.0687 (-0.249, 0.357)	reasonable	N
HadGEM2-ES_r1i1p1 WRF381P	good	good	0.258 (0.192, 0.294)	-0.145 (-0.516, 0.202)	good	Y
IPSL-CM5A-MR_r1i1p1 HIRHAM5	reasonable	good	0.172 (0.12, 0.206)	0.0561 (-0.483, 0.519)	reasonable	N
IPSL-CM5A-MR_r1i1p1 RACMO22E	good	good	0.219 (0.149, 0.259)	-0.149 (-0.597, 0.368)	good	Y
IPSL-CM5A-MR_r1i1p1 RCA4	good	good	0.226 (0.176, 0.265)	-0.014 (-0.47, 0.257)	good	Y
IPSL-CM5A-MR_r1i1p1 REMO2015	good	good	0.22 (0.148, 0.26)	-0.133 (-0.58, 0.673)	good	Y

IPSL-CM5A-MR_rli1p1 WRF381P	reasonable	good	0.169 (0.122, 0.205)	-0.296 (-0.668, -0.037)	reasonable	N
MIROC5_rli1p1 CCLM4-8-17	reasonable	good	0.255 (0.178, 0.307)	-0.225 (-0.696, 0.108)	reasonable	N
MIROC5_rli1p1 REMO2015	reasonable	reasonable	0.227 (0.15, 0.276)	-0.274 (-0.621, 0.0512)	reasonable	N
MIROC5_rli1p1 WRF361H	reasonable	good	0.194 (0.122, 0.243)	-0.238 (-0.726, 0.0832)	reasonable	N
MPI-ESM-LR_rli1p1 ALADIN63	bad	good	0.176 (0.129, 0.209)	-0.0355 (-0.398, 0.223)	bad	N
MPI-ESM-LR_rli1p1 CCLM4-8-17	good	good	0.21 (0.156, 0.246)	-0.0695 (-0.431, 0.138)	good	Y
MPI-ESM-LR_rli1p1 COSMO-crCLIM-v1-1	good	good	0.237 (0.166, 0.283)	-0.0816 (-0.577, 0.142)	good	Y
MPI-ESM-LR_rli1p1 HadREM3-GA7-05	good	good	0.179 (0.13, 0.208)	-0.0232 (-0.407, 0.419)	good	Y
MPI-ESM-LR_rli1p1 HIRHAM5	good	good	0.181 (0.133, 0.213)	-0.0776 (-0.448, 0.187)	good	Y
MPI-ESM-LR_rli1p1 RACMO22E	bad	good	0.232 (0.162, 0.279)	-0.155 (-0.683, 0.0768)	bad	N
MPI-ESM-LR_rli1p1 RCA4	good	good	0.243 (0.179, 0.276)	-0.134 (-0.416, 0.136)	good	Y
MPI-ESM-LR_rli1p1 RegCM4-6	good	good	0.232 (0.171, 0.273)	-0.0349 (-0.701, 0.342)	good	Y
MPI-ESM-LR_rli1p1 REMO2009	bad	good	0.214 (0.148, 0.257)	-0.116 (-0.574, 0.332)	bad	N
NorESM1-M_rli1p1 ALADIN63	reasonable	good	0.157 (0.0958, 0.19)	0.159 (-0.131, 0.961)	reasonable	N
NorESM1-M_rli1p1 COSMO-crCLIM-v1-1	reasonable	good	0.179 (0.118, 0.224)	0.297 (-0.0624, 0.953)	reasonable	N
NorESM1-M_rli1p1 HadREM3-GA7-05	reasonable	good	0.194 (0.118, 0.231)	-0.00168 (-0.238, 0.475)	reasonable	N
NorESM1-M_rli1p1 HIRHAM5	reasonable	good	0.153 (0.107, 0.181)	0.143 (-0.135, 0.552)	reasonable	N
NorESM1-M_rli1p1 RACMO22E	reasonable	good	0.167 (0.107, 0.206)	0.211 (-0.0308, 0.714)	reasonable	N
NorESM1-M_rli1p1 RCA4	good	good	0.149 (0.0812, 0.177)	0.117 (-0.129, 0.861)	bad	N
NorESM1-M_rli1p1 RegCM4-6	reasonable	good	0.199 (0.143, 0.238)	-0.275 (-0.694, 0.0792)	reasonable	N
NorESM1-M_rli1p1 REMO2015	reasonable	good	0.164 (0.115, 0.215)	0.109 (-0.422, 0.559)	reasonable	N
NorESM1-M_rli1p1 WRF381P	reasonable	good	0.247 (0.169, 0.29)	0.00894 (-0.294, 0.387)	reasonable	N
CMCC-CM2-HR4	bad	reasonable	0.208 (0.157, 0.253)	-0.184 (-0.554, 0.0846)	bad	N
CMCC-CM2-VHR4	bad	reasonable	0.197 (0.146, 0.235)	-0.071 (-0.42, 0.287)	bad	N
CNRM-CM6-1	good	good	0.176 (0.118, 0.212)	0.00968 (-0.313, 0.28)	duplicate	N

CNRM-CM6-1-HR	good	good	0.18 (0.117, 0.209)	-0.187 (-0.628, 0.405)	good	Y
EC-Earth3P	good	good	0.222 (0.137, 0.274)	-0.11 (-0.392, 0.468)	good	Y
EC-Earth3P-HR	reasonable	good	0.216 (0.15, 0.262)	-0.143 (-0.478, 0.256)	duplicate	N
HadGEM3-GC31-HM	good	good	0.195 (0.123, 0.244)	-0.111 (-0.371, 0.352)	good	Y
HadGEM3-GC31-LM	good	good	0.234 (0.173, 0.274)	-0.0778 (-0.443, 0.29)	bad	N
HadGEM3-GC31-MM	good	good	0.237 (0.175, 0.274)	-0.267 (-0.53, -0.0281)	duplicate	N
MPI-ESM1-2-HR	good	good	0.249 (0.167, 0.344)	0.097 (-0.662, 0.489)	duplicate	N
MPI-ESM1-2-XR	good	good	0.302 (0.238, 0.346)	-0.345 (-0.667, -0.0234)	reasonable	Y

A4 Estimated trends in climate models

Table A.4.1: Changes in intensity and probability ratios for what was in 2026 a 1-in-40-year $Rx1day$ -ONDJFM event over the southern study region, for observational datasets and for each model that passed evaluation: ‘past warming’: from the 1.3°C cooler preindustrial climate to the present; ‘future warming’: from the present to 2.6°C above preindustrial (1.3°C warmer than the present); ‘NAO’: comparing the 2026 normalised NAO state with a neutral state. All results are presented to 3 significant figures.

Obs / Models	Change in intensity (%)			Probability ratio		
	Past warming	Future warming	NAO	Past warming	Future warming	NAO
E-Obs	49.2 (23.6, 77.3)	-	4.44 (-1.13, 9.33)	48.4 (2.62, Inf)	-	1.42 (0.929, 4.57)
ERA5	23 (-0.257, 47.7)	-	5.36 (0.664, 9.58)	64.9 (0.983, Inf)	-	2.1 (1.15, 29.2)
CNRM-CM5_rli1p1 ALADIN53	12.6 (-11.3, 44.1)	4.72 (-2.63, 12.1)	-0.496 (-5.89, 4.96)	2.54 (0.346, 434)	1.49 (0.815, 2.71)	0.964 (0.649, 1.47)
CNRM-CM5_rli1p1 HIRHAM5	4.06 (-16.5, 31.8)	4.01 (-4.79, 11.4)	7.47 (1.6, 13.2)	1.41 (0.272, 3220)	1.42 (0.698, 3.14)	1.91 (1.19, 4)
CNRM-CM5_rli1p1 RACMO22E	-3.08 (-20.7, 20.4)	2.79 (-4.97, 10.6)	4.32 (-1.29, 8.7)	0.722 (0.139, Inf)	1.31 (0.599, 3.82)	1.61 (0.792, 4.33)
CNRM-CM5_rli1p1 RegCM4-6	12.3 (-12.2, 37.6)	7.51 (0.663, 13.9)	5.54 (0.385, 13.4)	3.07 (0.474, Inf)	1.88 (1.06, 4.04)	1.65 (1.03, 6.54)
CNRM-CM5_rli1p1 REMO2015	8.3 (-16.3, 39.7)	7.09 (0.0937, 13.6)	6.82 (1.92, 12.3)	2.62 (0.245, Inf)	1.91 (1.01, 3.97)	2.19 (1.22, 7.44)
CNRM-CM5_rli1p1 WRF381P	-5.47 (-27.6, 29.2)	4.49 (-3.48, 10.8)	2.89 (-2.44, 8.19)	0.539 (0.0965, Inf)	1.61 (0.733, 3.37)	1.43 (0.686, 3.16)
EC-EARTH_r12i1p1 WRF361H	18.2 (-11.9, 55.7)	7.01 (0.127, 14)	2.48 (-3.42, 7.88)	5.98 (0.353, Inf)	2.01 (1.02, 4.04)	1.26 (0.568, 2.58)

IPSL-CM5A-MR_rli1p1 RACMO22E	1.62 (-19.6, 22.7)	-7.78 (-15, -1.81)	9.57 (4.98, 13.6)	1.12 (0.295, 6.9)	0.586 (0.354, 0.87)	1.94 (1.29, 4.36)
MPI-ESM-LR_rli1p1 HadREM3-GA7-05	1.13 (-12.3, 18.4)	-2.64 (-8.72, 4.57)	3.89 (-0.639, 8.9)	1.12 (0.238, 56.9)	0.745 (0.339, 2.81)	1.49 (0.861, 3.92)
MPI-ESM-LR_rli1p1 HIRHAM5	1.42 (-9.88, 10.8)	0.211 (-6.08, 6.01)	2.29 (-0.352, 8.59)	1.47 (0.144, 17100)	1.03 (0.22, 2.5)	1.92 (0.875, 184)
MPI-ESM-LR_rli1p1 RCA4	-7.63 (-22.4, 9.8)	-6.86 (-13.7, -0.717)	4.65 (-1.56, 12.3)	0.474 (0.087, 2.71)	0.447 (0.136, 0.924)	1.61 (0.757, 6.1)
MPI-ESM-LR_rli1p1 RegCM4-6	-0.785 (-16.5, 12.5)	0.166 (-6.79, 7.14)	-0.0826 (-4.67, 7.48)	0.855 (0.0801, Inf)	1.02 (0.462, 2.77)	0.983 (0.214, 7.17)
CMCC-CM2-VHR4	-3.97 (-13.9, 17.5)	-8.32 (-18.5, 4.51)	11.7 (5.55, 19)	0.686 (0.237, 26.8)	0.481 (0.171, 1.68)	3.32 (1.91, 12.4)
EC-Earth3P	3.38 (-12, 23.9)	-2.96 (-15.9, 8.89)	5.02 (1.26, 9.52)	1.34 (0.337, 12.1)	0.758 (0.233, 2.73)	1.54 (1.13, 3.13)
HadGEM3-GC31-MM	2.58 (-12.1, 26.2)	10.5 (-1.96, 19.5)	8.32 (3.46, 13.6)	1.32 (0.16, 65.9)	3.17 (0.784, 8.96)	2.55 (1.44, Inf)
MPI-ESM1-2-XR	-1.6 (-11.5, 24.8)	1.46 (-12, 14.5)	16 (9.69, 23.9)	0.869 (0.282, 34.1)	1.12 (0.34, 3.5)	4.62 (2.04, Inf)

Table A.4.2: Changes in intensity and probability ratios for what was in 2026 a 1-in-5-year Rx1day-ONDJFM event over the northern study region, for observational datasets and for each model that passed evaluation: ‘past warming’: from the 1.3°C cooler preindustrial climate to the present; ‘future warming’: from the present to 2.6°C above preindustrial (1.3°C warmer than the present); ‘NAO’: comparing the 2026 normalised NAO state with a neutral state. All results are presented to 3 significant figures.

Obs / Models	Change in intensity (%)			Probability ratio		
	Past warming	Future warming	NAO	Past warming	Future warming	NAO
E-Obs	39.3 (16.4, 70.5)	-	2.66 (-1.04, 6.67)	7.12 (2.71, 46.9)	-	1.1 (0.958, 1.35)
ERA5	19.1 (-1.01, 47.3)	-	1.61 (-1.75, 5.29)	3.45 (0.925, Inf)	-	1.09 (0.888, 1.36)
CNRM-CM5_rli1p1 ALADIN53	1.1 (-17.7, 21.8)	6.09 (-0.0448, 11.4)	4.3 (0.0579, 8.22)	1.08 (0.354, 5.04)	1.45 (0.997, 1.98)	1.35 (1, 1.99)
CNRM-CM5_rli1p1 HIRHAM5	2.01 (-13.8, 19.7)	7.15 (1.04, 12)	3.13 (-1.19, 7.63)	1.16 (0.431, 6.86)	1.58 (1.08, 2.11)	1.26 (0.911, 1.85)
CNRM-CM5_rli1p1 RACMO22E	-0.609 (-16.5, 19.1)	6.49 (0.7, 12.1)	2.15 (-2.1, 6.49)	0.956 (0.379, 10.1)	1.49 (1.05, 2.05)	1.18 (0.859, 1.69)
CNRM-CM5_rli1p1 RegCM4-6	-0.99 (-21.9, 25.3)	5.98 (-0.424, 11.9)	3.04 (-1.96, 8.48)	0.935 (0.311, 9.34)	1.47 (0.969, 2.1)	1.24 (0.875, 2.28)
CNRM-CM5_rli1p1 REMO2015	3.37 (-11.3, 21.5)	8.03 (2.65, 12.3)	3.51 (-0.931, 8.29)	1.3 (0.473, 10.5)	1.71 (1.23, 2.17)	1.32 (0.928, 1.92)
CNRM-CM5_rli1p1 WRF381P	10.4 (-6.93, 30.7)	7.85 (1.44, 13.4)	-0.527 (-4.51, 4.16)	1.99 (0.668, 12.8)	1.54 (1.09, 2.08)	0.968 (0.733, 1.29)
HadGEM2-ES_rli1p1 COSMO-crCLIM-v1-1	5.98 (-10.7, 25.2)	0.413 (-5.2, 6.46)	3.6 (-0.553, 8.41)	1.4 (0.577, 33.6)	1.02 (0.752, 1.38)	1.22 (0.969, 1.72)

HadGEM2-ES_rli1p1 HadREM3-GA7-05	7.49 (-6.57, 25.8)	0.279 (-4.75, 5.44)	4.57 (0.816, 9.15)	1.55 (0.688, 8.4)	1.02 (0.745, 1.34)	1.3 (1.05, 1.82)
HadGEM2-ES_rli1p1 WRF381P	10.5 (-7.21, 26.8)	3.27 (-2.16, 7.94)	1.54 (-2.56, 5.83)	1.99 (0.683, 37.4)	1.2 (0.882, 1.58)	1.1 (0.848, 1.53)
IPSL-CM5A-MR_rli1p1 1 RACMO22E	13.8 (-2.69, 34.7)	-0.0478 (-4.86, 4.71)	4.69 (0.655, 8.7)	2.36 (0.854, 43.6)	0.997 (0.746, 1.29)	1.32 (1.04, 1.76)
IPSL-CM5A-MR_rli1p1 1 RCA4	22.9 (5.52, 43.5)	4.57 (-1.15, 10.2)	2.72 (-2.12, 7.57)	4.18 (1.45, Inf)	1.26 (0.943, 1.72)	1.17 (0.876, 1.74)
IPSL-CM5A-MR_rli1p1 1 REMO2015	19.3 (0.395, 39.2)	2.65 (-2.31, 7.92)	4.97 (0.404, 9.71)	3.05 (1.02, 33)	1.15 (0.878, 1.51)	1.32 (1.03, 1.62)
MPI-ESM-LR_rli1p1 CCLM4-8-17	12.4 (0.203, 26.3)	6.57 (2.14, 11.7)	2.3 (-1.68, 6.43)	2.49 (1.01, 860)	1.52 (1.14, 2.22)	1.17 (0.886, 1.56)
MPI-ESM-LR_rli1p1 COSMO-crCLIM-v1-1	7.28 (-5.76, 20.8)	3.82 (-1.8, 9.26)	0.999 (-3.23, 6.3)	1.62 (0.697, 6.4)	1.27 (0.887, 1.83)	1.07 (0.805, 1.56)
MPI-ESM-LR_rli1p1 HadREM3-GA7-05	9.64 (-3.83, 25.4)	5.55 (0.489, 10.3)	0.316 (-3.98, 5.16)	2.11 (0.741, 13.2)	1.46 (1.04, 1.98)	1.02 (0.745, 1.57)
MPI-ESM-LR_rli1p1 HIRHAM5	5.14 (-6.8, 17.8)	5.91 (1.08, 10.1)	0.617 (-3.66, 4.61)	1.49 (0.588, 4.84)	1.49 (1.08, 2.05)	1.05 (0.75, 1.46)
MPI-ESM-LR_rli1p1 RCA4	9.1 (-13.7, 33)	8.43 (2.05, 15.3)	-0.104 (-5.57, 7.53)	1.77 (0.449, 11)	1.6 (1.14, 2.27)	0.994 (0.712, 1.77)
MPI-ESM-LR_rli1p1 RegCM4-6	23.2 (-5.59, 50.9)	6.13 (-1.51, 15.6)	-2.93 (-9.13, 2.69)	3.86 (0.785, Inf)	1.4 (0.92, 2.37)	0.856 (0.642, 1.18)
CNRM-CM6-1-HR	9.46 (-5.9, 27.5)	4.94 (-3.87, 13.5)	2.89 (-2.42, 8.24)	2 (0.674, 7.61)	1.37 (0.768, 2.32)	1.23 (0.857, 2.01)
EC-Earth3P	-8.11 (-12.6, 11.5)	-1.81 (-12.5, 8.53)	-0.448 (-3.29, 3.56)	0.627 (0.472, 2.23)	0.894 (0.44, 1.69)	0.973 (0.814, 1.24)
HadGEM3-GC31-HM	-0.795 (-7.47, 23.4)	-6.66 (-11.8, 2.21)	5.33 (0.54, 10.5)	0.949 (0.62, 10.8)	0.644 (0.439, 1.15)	1.46 (1.04, 2.28)
MPI-ESM1-2-XR	-0.708 (-6.53, 20.2)	1.94 (-8.69, 13.3)	1.95 (-2.94, 6.7)	0.954 (0.661, 13.3)	1.11 (0.486, 1.95)	1.15 (0.804, 1.61)