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ORIGINAL ARTICLE

On the Effect of Classical Versus Geopotential-jet Weather Regimes on Wintertime Rainfall Variability: Case of Morocco

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Abstract

Rainfall variability in North-West Africa, in particular Morocco, has profound socioeconomic impacts, with climate projections indicating a continued decrease in precipitation. However, interpreting rainfall projections is challenging due to substantial biases in current climate models, partly resulting from their low resolutions compared to precipitation scales. Large-scale North Atlantic atmospheric dynamics, e.g., the NAO, significantly impact Moroccan wintertime rainfall variability. As models resolve these large-scale dynamics comparatively well, we investigate their use as dynamical proxies for Moroccan rainfall variability, from the perspective of Euro-Atlantic weather regimes (WRs). The four classical WRs have previously shown limitations when used for downscaling Moroccan precipitation in the context of climate change (future climate simulations). Here we adopt recently-introduced 'Geopotential-Jet Regimes' (GJRs), using three and seven clusters, and compare their connection to observed Moroccan rainfall to those of classical WRs. We highlight that the NAO- regime is the main driver of winter rainfall in northwestern Morocco, producing rainfall levels approximately twice the climatological average, and that Scandinavian and European blocking have dramatically different rainfall teleconnections in North Africa. By comparing station data with regime-based reconstructions, this study finds significant correlations between North Atlantic WRs and winter rainfall in Morocco's most rainy and populous Northwestern region. Correlations average is around 0.6 for the three-GJR framework in the case of mean rainfall and the wet days fraction, it reaches 0.7 at some stations. The simpler three-regime GJR framework proves at least as effective as the four classical WRs in the historical period explaining about 36% to 49% of the total precipitation variance in nearly all the stations of the Northwest. This highlights their usefulness when combined with their previously demonstrated stable, well-reproduced regimes in CMIP6 simulations. This work therefore suggests GJRs may offer unique insights for improving projections of future rainfall changes in North-West Africa which we will pursue in future work.

Keywords Classical weather regimes · Extreme events · Geopotential-jet weather regimes · Morocco · NAO · North-Atlantic atmospheric dynamics · Regime-based rainfall reconstructions · Wintertime rainfall variability

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1 Introduction

Stress on fresh-water availability makes Morocco one of the most vulnerable countries to climate change in the Mediterranean and North Africa (World Bank,2022a; Diffenbaugh and Giorgi 2012; Schilling et al. 2020). Morocco's agricultural sector in particular is highly dependent on rainfall, with rainfed areas representing 80% of all arable land (World Bank, 2022b). In recent years, Morocco has experienced recurrent drought with serious negative impacts on important socio-economic sectors such as water and agriculture (e.g., Benassi 2008; Verner et al. 2018). On another hand, heavy rainfall events continue to cause devastating floods in the country with several notable late Autumn and wintertime extremes in the last three decades unfortunately causing significant loss of life and property (Driouech et al. 2020a; Loudyi et al. 2022; Sahlaoui et al. 2022). Current climate projections for the region anticipate a continuing drying trend (Arjdal et al. 2023; Balhane et al. 2022; Betts et al. 2018; Driouech et al. 2010a, 2020b; Tramblay et al. 2016) with less certain changes in high precipitation events. Understanding the impact of climate change on rainfall in Morocco is therefore of utmost importance.

In this study we will adopt a weather regime (WR) perspective and assess the suitability of different regime frameworks for explaining historical wintertime rainfall variability in Morocco. In particular, we will explore the added value of the recently-introduced geopotential jet regime framework which has been developed specifically with climate applications in mind. Through our comparison of the statistics and dynamics of regime-rainfall connections in observations, we provide the most thorough exploration of regime impacts on Morocco to date, and suggest a framework for application to precipitation trend analysis in climate projections.

WRs summarize the large-scale atmospheric evolution in terms of transitions between a finite number of recurrent, persistent, and/or quasi-stationary large-scale patterns of pressure and circulation anomalies over wide geographical sareas. They thereby granularize the variability captured by large scale climate modes such as the North Atlantic Oscillation (NAO) which plays a substantial role in determining winter Moroccan precipitation and surface temperatures (Driouech et al. 2010a; El Hamly et al. 1997; Hurrell 1995; Knippertz et al. 2003; Trigo et al. 2004; Ward et al. 1999). The relationship between a set of four North Atlantic WRs and local precipitation in Morocco was investigated for the first time by (Driouech et al. 2010b), which showed significant correlations between WRs and precipitation characteristics especially in the region west of the Atlas Mountains (see Fig. 1 hereafter). Extending the domain to include the Mediterranean, (Gadouali et al. 2020) confirmed the influence of the Atlantic WRs.

In theory, the WR perspective could help address the mismatch of scales between climate model resolution and the scale of rainfall processes. By identifying observed statistical relations between regimes and rainfall, climate models can be used to diagnose future changes in the large-scale regimes which they can resolve, and these can then be statistically mapped to changes in local rainfall. Just such a regime-based statistical downscaling of Moroccan rainfall was investigated by (Driouech et al. 2010a), for a set of climate models, but there it was found that projected changes in rainfall within each regime were much larger than the projected changes in regimes themselves. They therefore concluded that the regime-rainfall linkage in the current climate may not be valid in the future, challenging this approach. More recently, (Dorrington and Strommen 2020) highlighted that classical approaches to identifying weather regimes (hereafter classical WRs) were highly unstable to sampling variability, and emphasized the negative impacts this instability can have when applying WRs approaches to climate models. To address this, (Dorrington and Strommen 2020) proposed a new regime framework known as 'Geopotential-Jet Regimes' (hereafter GJRs). This approach integrates jet and geopotential height data and exhibits regimes with remarkably little historical variability in the regime patterns – a necessary prerequisite for climate change analysis. They filtered out the linear influence of Atlantic jet speed on the geopotential height field before clustering, thereby

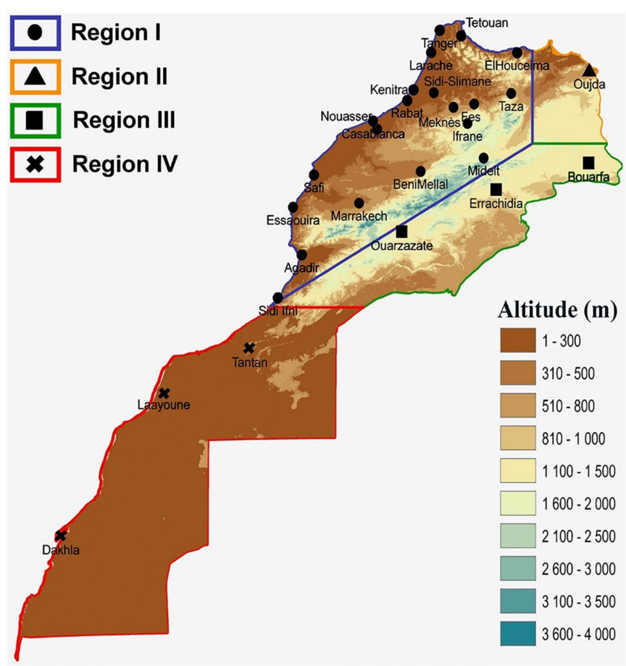

Fig. 1 Geographical distribution and altitudes of the meteorological stations utilized in the study, schematically delineating the four climatic regions by distinct color segments (based on Balhane et al. 2024)

focusing on the impact of fundamentally nonlinear jet-latitude variations. In support of this approach for Moroccan applications, (Barriopedro et al. 2023) found that the latitudinal parameters of the Eddy-driven jet are the leading predictors of precipitation patterns in southern Europe and northern Morocco. Using this new framework, (Dorrington et al. 2022b) were able to isolate significant signals in future regime changes. Further, (Dorrington et al. 2022a) showed that CMIP6 models have substantially more realistic regimes than the previous generation of models (e.g., CMIP5). Improved models and a more stable regime framework may therefore allow for an effective regime-based constraint on future Moroccan precipitation.

Before such a revised approach can be applied to the climate projection task, we must validate its utility in a historical context, which is the task we undertake in this paper. Thus, we compare how well classical and geopotential jet regimes explain rainfall characteristics in Morocco using observation data from 27 weather stations, considering both average and extreme rainfall events. We make the comparison against the well-understood and commonly used four classical weather regimes (Michelangeli et al. 1995) to assess the quality of the link between GJRs and Moroccan surface precipitation in the historical period. In Sect. 2 we describe the data and our methodology, Sect. 3 focuses on the weather regimes and the relationship with precipitation, in Sect. 4 we analyze the skills of regime-based rainfall reconstructions and dedicate Sect. 5 to discussion. Finally, main conclusions are drawn in Sect. 6.

2 Data and Methodology

2.1 Data

To assess the link between weather regimes and local precipitation, we use daily rainfall data from 27 meteorological stations of the Moroccan National Meteorological Service (DGM) – locations shown in Fig. 1. The data quality has been controlled by the DGM to identify suspicious or unreasonable values before being publicly available. In 24 stations, the time series cover the period 1979–2014, Dakhla and Sidi Slimane stations cover the period 1980–2014, and Bouarfa's time series 1981–2014. Missing data do not exceed 0.7% in each of the stations, they were just ignored, and no gap-filling has been done. Days with missing data were discarded from all time-series. Despite an inhomogeneous spatial coverage that favors the northwestern part of the country, the stations cover the main climatic regions identified by previous studies (El Hamly et al. 1997; Knippertz et al. 2003). Region I representing the northwest of the country is limited to the West by the Atlantic Ocean. Region II corresponds to the northeast of Morocco and is limited to the North by the Mediterranean Sea. It is represented only by one station (Oujda), but it is a well-established reference in regional studies (e.g., Knippertz et al. 2003; Driouech et al. 2009). Furthermore, this study focuses on the influence of Euro-Atlantic weather regimes, which are large-scale atmospheric patterns with widespread impacts. Region III covers the southeast of the Atlas Mountains. The fourth Region (IV) encompasses the Sahara Desert to the South (Balhane et al. 2024; Driouech et al. 2020b).

We consider the winter (December-February (DJF)) period, which coincides with the core of the Moroccan rainy season, making it the most impactful for agriculture and several related socioeconomic developments in the country. In addition to considering daily rainfall amounts, we assess the number of 'wet days' and 'extreme wet days', defined as days with total precipitation exceeding 1 mm and the station's 95th percentile of rainfall respectively.

To identify the WRs related large-scale circulation patterns in the atmosphere, we make use of the commonly used dynamic and thermal fields, corresponding to the 500 hPa geopotential height (Z500), the zonal and meridional wind components at 850 hPa (U850, V850), the 850 hPa temperature (T850), the mean sea level pressure (MSLP), and the relative humidity at 850 hPa (RH850). These data are derived from the ERA5 reanalysis (Hersbach et al. 2020), downloaded at 0.25° horizontal resolution for DJF over the 1979–2014 period.

2.2 Methodology

The focus of this study on Euro-Atlantic weather regimes is based on several considerations. Firstly, WRs have a substantial influence on Moroccan rainfall during winter, when the majority of precipitation occurs. Previous studies have shown that most of the variability in Moroccan winter precipitation can be attributed to the North Atlantic Oscillation (Lamb and Peppler 1987; El Hamly et al. 1997; Knippertz et al. 2003; Driouech et al. 2010b). Thus, by focusing on Euro-Atlantic WRs, we aim to capture the dominant large-scale drivers of Moroccan rainfall, particularly in the northwestern part of the country; the most humid and populated one. Secondly, WRs offer a well-established framework that has been extensively studied and validated in the context of North Atlantic and European weather patterns. This allows us to compare our findings with existing literature and understand how these large-scale patterns influence Moroccan rainfall. Several previous studies focused on Euro-Atlantic variability, so linking regimes to Moroccan rainfall helps leverage that existing work. Furthermore, our primary objective is to compare the new Euro-Atlantic geopotential-jet approach with the classical one.

Weather regimes are computed over the North Atlantic domain (30°N-90°N, 80°W-40°E) following two approaches:

1. The **classical weather regimes** were computed by applying a K-means clustering algorithm to the first ten principal components (PCs) of 500 hPa geopotential height data as done in several previous studies (Driouech et al. 2010a; Michelangeli et al. 1995**).** The ten computed PCs explain 83.5% of the total variance.
2. **Geopotential-jet regimes** undergo an additional filtering step before clustering, as motivated in (Dorrington and Strommen 2020). The speed of the low-level Euro-Atlantic jet is computed, defined as the meridional maximum of 5-day rolling mean zonally averaged zonal 850 hPa wind over the domain (15°N-75°N, 60°W-0°W) as in (Parker et al. 2019). This jet speed index is then regressed out of each Z500 PC, producing residual PCs that describe the variability of geopotential height that cannot be explained by linear variations in jet strength. These are then clustered to produce geopotential-jet regimes, which are more robust to sampling variability and are better resolved by climate models (Dorrington et al. 2022a), and so are better suited to exploring forced trends (Dorrington et al. 2022b**).** A correlation analysis between local rainfall, measured at each of the 27 stations, and the jet speed index has been conducted, revealing no discernible correlation between these two variables. This finding supports the adoption of the GJRs approach, which removes the jet speed influence, particularly in the context of precipitation analysis. Importantly, flow-composites for GJRs are always reconstructed in the full geopotential height field, ensuring comparability with the classical WRs.

2.2.1 Neutral days within the dataset

Considering only a finite number of WRs provides only an approximation of the continuum of weather patterns. Some days will resemble none of the defined regimes yet by default are assigned to the regime to which they are most similar. These days correspond to transition days or infrequent flow configurations. We consider the benefits of excluding such days, by putting them in a "*neutral state"* or a "*no-regime*" category. Concretely, a day is classified as *neutral* if the pattern correlation between the daily Z500 field and the regime composites is below 0.4, following (Dorrington et al. 2022a). As this adds methodological complexity, we discuss the added value of including a *neutral state* category for both classical and geopotential-jet regimes in Sect. 3.1.

2.2.2 Regime reconstruction of rainfall

To assess to what extent WRs can be used to reproduce Moroccan rainfall, we use a seasonal reconstruction approach applied to three rainfall indices: daily Mean Rainfall (MR), Wet Days Fraction (WDF), Extreme Wet Days Fraction (EWDF). First, we define regime composites as the average value of the rainfall index over all days in a regime k, denoted as R_k. We produce a regime-based reconstruction of a given rainfall index by taking an average of these regime composites, weighted by the occurrence fraction of each regime in a given year, y, denoted as $O_{k,y}$:

$$R_{reconstructed,y} = \sum_k O_{k,y} R_k$$

This method allows us to approximate a season's rainfall based on the frequency of each WR and their associated rainfall characteristics. The accuracy of this reconstruction will be used to assess the usefulness of a given regime framework for understanding Moroccan precipitation.

3 Links Between Weather Regimes and Local Precipitation

3.1 Weather Regime Computation

Z500 composites for both classical and geopotential-jet regimes are shown in Fig. 2, using 4 clusters for classical WRs, as in (Cassou 2008; Driouech et al. 2010a; Michel and Rivière 2011; Michelangeli et al. 1995), and using 3 and 7 clusters for GJRs which were found to be the most reproducible patterns in reanalyses and models in (Dorrington et al. 2022a).

The four classical WRs correspond to:

- The Greenland blocking or negative phase of the NAO regime (NAO−), characterized by a steered southward Icelandic low allowing more Atlantic storms to reach southern Europe and the Mediterranean.
- The Scandinavian blocking regime (Sc BLK), characterized by a persistent high over northern Europe and Scandinavia and a low shifted westward in the Atlantic.
- The Atlantic ridge (AR) regime that corresponds to a strengthened and moved northward Azores high.
- The zonal or positive NAO regime (NAO+), associated on the one hand with a spread and reinforced Azores high that extends to the east across North Africa and southern Europe, and a deep Icelandic low with intensified westerly flow over the northeast Atlantic and the European continent, resulting in more frequent and

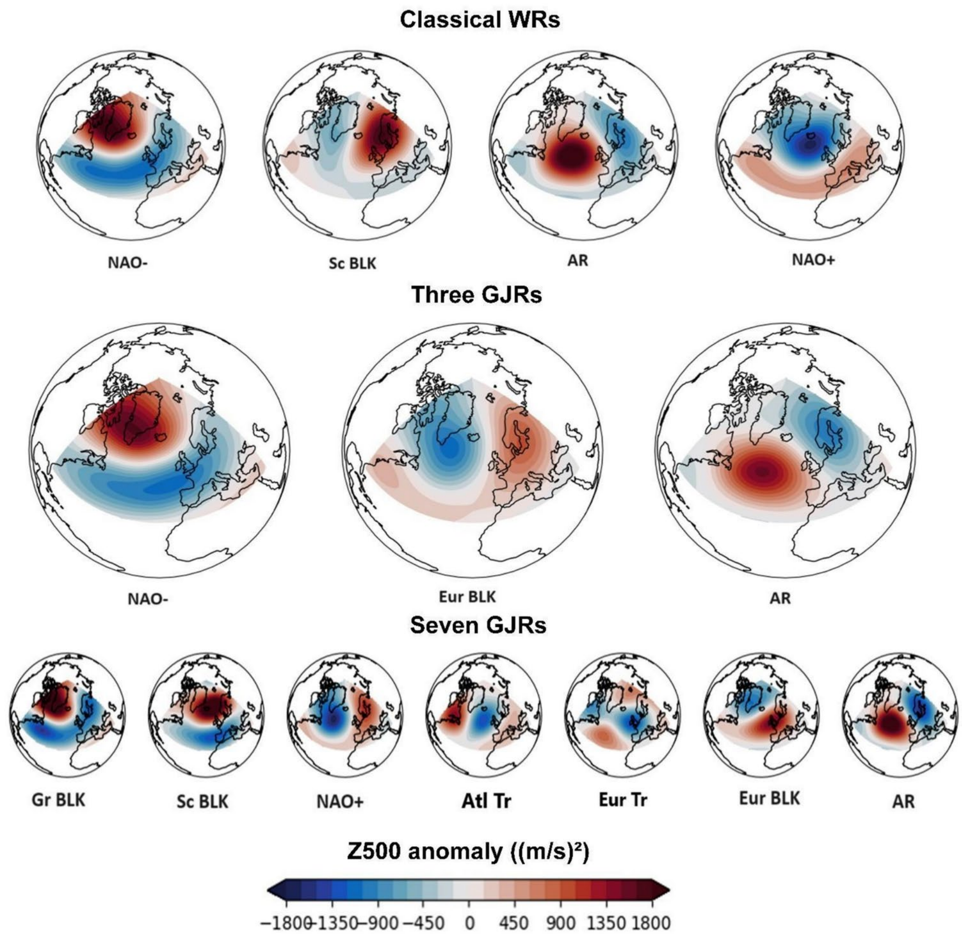

Fig. 2 Wintertime North Atlantic Weather Regimes are obtained from geopotential height anomalies at 500 hPa for the four classical WRs (top panel), the three GJRs (middle), and the seven GJRs (bottom) configurations. Red color corresponds to positive geopotential height anomalies, and blue color corresponds to negative anomalies. The darker the color, the higher the absolute value of the anomaly

stronger winter storms crossing the Atlantic Ocean on a more northerly track.

The 3 GJRs are marked by:

- A negative NAO regime (NAO−) very comparable to the classical NAO−.
- A European blocking regime (Eur BLK) which is less dominated by the anticyclonic anomaly than the classical Scandinavian BLK. Over Morocco, the two BLK regimes have, notably, different signed anomalies, although both are relatively weak.
- An Atlantic ridge (AR) regime that is less dominated by the anticyclonic anomaly than the classical AR. Notably, both AR regimes exhibit different signed anomalies over Morocco, although their effects are relatively subtle.

In the 7 GJRs, we distinguish three regimes dominated by a cyclonic anomaly: the zonal regime (NAO+), the European Trough (Eur Tr), and the Atlantic Trough (Atl Tr). In contrast, the four other regimes are dominated by an anticyclonic anomaly: the Scandinavian Blocking (Sc BLK), the Atlantic Ridge (AR), the European Blocking (Eur BLK), and the Greenland Blocking (Gr BLK). These patterns offer more nuanced insights into the atmospheric dynamics influencing Morocco's climate. There are similarities in the patterns of the seven GJRs to the classical 7-regime frameworks of Gadouali et al. (2020) and Grams et al. (2017). However, as Dorrington et al. (2022b) found that 7 classical WRs do not provide the same interdecadal stability as using GJR regimes, we find value in introducing these new patterns here.

Our analysis delved into whether accounting for 'neutral' days —days that do not align with any defined weather regime—could enhance the understanding of weather patterns' impact on rainfall in Morocco. We discovered that removing neutral days from the computation of WRs and putting them into a distinct 'neutral category' improves the explanation of rainfall variability in the eastern parts of Morocco (Regions II and III) when employing a limited number of regimes. However, this additional categorization did not show a similar benefit in a more detailed seven-regime framework. This is illustrated in Figure S1 in the supplementary material for the geopotential-jet three- and seven-clusters, and the classical four-clusters respectively. For this study, we therefore compared three configurations:

Table 1 Weather regime occurrences in the K4 and K3 frameworks

	NAO+	NAO−	AR	BLK	No-regime
K3	/	17%	15%	21%	47%
K4	23%	16%	14%	17%	30%

- K3 Configuration: 3 geopotential-jet regimes derived from days not classified as neutral.
- K4 Configuration: 4 classical weather regimes, also excluding neutral days.
- K7 Configuration: 7 geopotential-jet weather regimes, using the complete dataset, inclusive of neutral days.

Table 1 presents the frequency of each WR and of the neutral category 'no-regime' for K3 and K4 configurations. Frequencies of WRs in the K7 framework are shown in Table S1 in the Supplementary Material. Understanding the frequencies of these WRs can provide valuable insights into the dominant atmospheric patterns, which is crucial for understanding and predicting regional weather and climate phenomena. The NAO + regime is the most prevalent in the classical K4 framework, occurring 23% of the time, while the Eur BLK regime dominates the K3 framework with a 21% frequency. The NAO- and AR regimes show similar frequencies across both frameworks. However, the frequencies of blocking regimes are quite different, with K3 BLK at 21% and K4 BLK at 17%, reflecting distinct geopotential height anomaly patterns over North Africa as shown in Fig. 2. Interestingly, the frequency of the 'no-regime' category is lower in K4 (30%) compared to K3 (47%) which can be attributed to the increased regime count capturing more variability and the GJR's exclusion of days with strong jet influences. Tracking K4 NAO + days reveals they mainly emerge in the K3 framework as BLK (47%) and neutral (44%) days. The remaining 9% of NAO + days appear as AR days.

3.2 Weather Regimes' Contribution to Moroccan Rainfall and Associated Dynamics

In this subsection, we analyze the influence of WRs on winter rainfall at the 27 meteorological stations by comparing their contributions to the winter climatological averages computed over the studied period (1979–2014). Figures 3, 4, and 5 show the contributions of each WR in the K3 and K4 frameworks to the mean rainfall (MR), wet days fraction (WDF), and extreme wet days fraction (EWDF). In these Figures, a contribution of 100% means that the regime occurs twice as frequently as its climatological average, a value close to 0% indicates that the regime occurs as frequently as the climatological mean, while a value of − 100% indicates that the regime does not occur. For a comprehensive overview, these contributions are averaged by egion and summarized in Tables S2 and S3 in the Supplementary Material for the K4 and K3 frameworks, respectively. We exclude the K7 framework from this analysis because, as will be shown in Sect. 4, we find the simpler K3 framework gives equally good results.

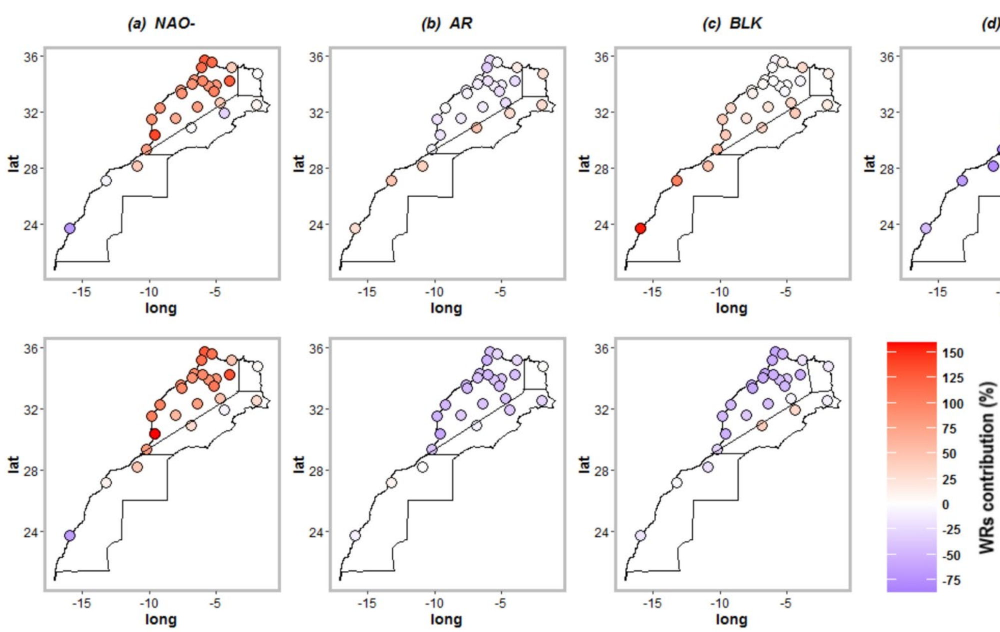

Fig. 3 Contribution in percentage of the **K4 WRs** (top) and **K3 WRs** (bottom) in 'mean rainfall' index over Morocco compared to the climatological average. A percentage of 100% indicates that the regime gives rainfall amounts twice the climatological average, a value close to 0% indicates that the regime gives rainfall amounts close to the climatological ones, while a value of − 100% indicates that the regime does not occur. Segments separate the four Regions as shown in Fig. 1

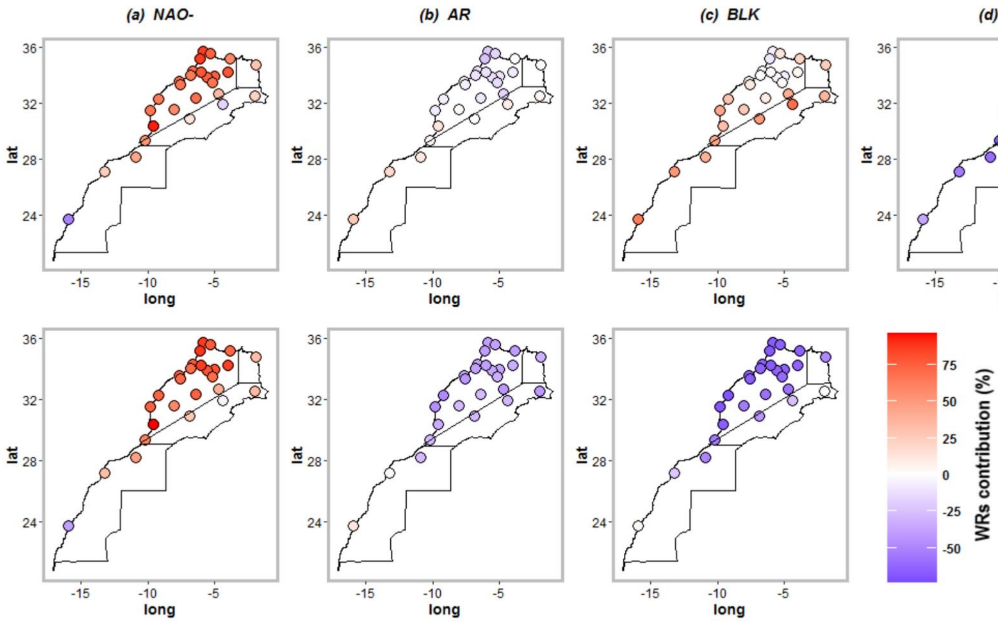

Fig. 4 As Fig. 3, but for 'wet days fraction' index

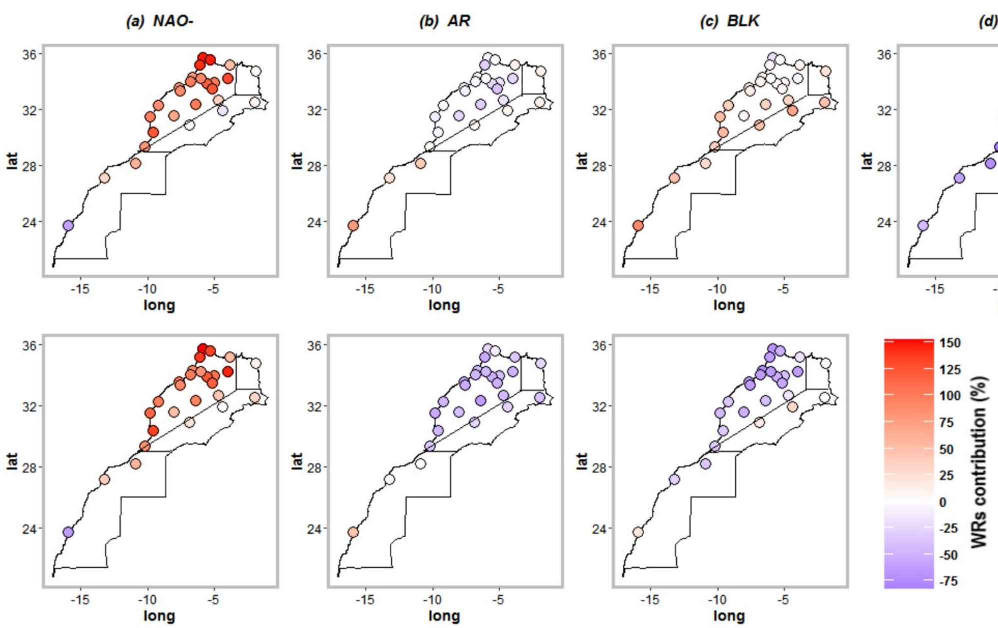

Fig. 5 As Fig. 3, but for 'extreme wet days fraction' index

The NAO- regime is very distinctive and its rainfall footprint is equivalent in both classical and GJR approaches for the three indices. It consistently signals wetter conditions in the Atlantic-facing Region I, and to a lesser extent in northern Region IV, as shown in Figs. 3a, 4a, and 5a. NAO- average contribution to MR reaches up to 200% of the climatology in Region I and 140% in northern Region IV. Contributions to both WDF and EWDF are nearing 200% of the climatological average in Region I. However, this regime's influence is weak and closer to climatology in Regions II and III. Interestingly, the NAO- contributions to MR and WDF indices dip below 50% of the climatology at Dakhla station which is located on a narrow peninsula of the Atlantic Coast, far in the South. This indicates that the southernmost area of Morocco mostly escapes the influence of North-Atlantic regimes, and underscores the limitations of the WRs approach at these latitudes. This is consistent with the boundary of influence of the mid-latitude eddy-driven jet, which even in its southerly mode rarely extends beyond 25°N (Madonna et al. 2017).

In line with prior studies (Driouech et al. 2010a; Gadouali et al. 2020), the classical NAO+regime is linked with widespread drier conditions across Morocco, reflecting similar patterns for all rainfall indices, as depicted in Figs. 3d, 4d, and 5d. The most significant rainfall deficits are observed in Region I, where the averaged contribution in MR falls below 40% of the climatological mean (Tab. S2).

The impact of the BLK regime on Moroccan rainfall indices is highly variable between the K3 and K4 regime frameworks, as indicated in Figs. 3c, 4c, and 5c. The K4 BLK regime generally correlates with wetter conditions than climatology across Morocco. Notably, in Region IV, contributions to MR rise to approximately 200% of the climatology, although we note that this climatological value is in any case small in the south, with annual mean rainfall of 30 mm in Dakhla and 48 mm in Laayoune. In Region III, between 28°N and 32°N, contributions to WDF exceed approximately 150% of the climatology. Conversely, the K3 BLK regime is linked to a WDF significantly lower than the climatology (approximately 50%), closer to the K4 NAO+pattern. For both the MR and EWDF indices, contributions are negative in Region I, moderately positive in Region III, and close to climatological values in other Regions. These disparities can be explained heuristically, by reference to the general circulation pattern depicted in Fig. 2. In this Figure, the K4 BLK regime is characterized by relatively low geopotential height anomalies over Morocco, fostering increased rainfall along a southwest/northeast axis. In contrast, the K3 BLK regime is distinguished by relatively positive geopotential height anomalies over North Africa, typically resulting in drier conditions.

The impact of the AR regime on rainfall indices also varies between the two approaches, although not quite so dramatically, as illustrated in Figs. 3b, 4b, and 5b. In the K3 framework, AR generally correlates with drier conditions in the northern half of the country, while remaining close to climatological averages south of 28°N. However, in the K4 configuration, AR is linked to relatively wetter conditions in Regions II, III, and IV, but tends to induce quite drier conditions in Region I. This effect is consistent across all three studied indices. Referring to Fig. 2, the AR regime in the K4 approach is associated with a relatively low geopotential anomaly over northern Morocco, forming an extension of the cyclonic geopotential height anomaly centered on western Russia. On the other hand, in the K3 approach, this regime is linked to a fairly neutral geopotential height anomaly over northern Africa. This different feature of large dynamic field anomalies over Morocco creates different impacts of the AR regime on precipitation in both approaches.

To better understand the similarities observed in the NAO- regime, as well as the above-depicted differences in the contributions of the BLK and AR regimes to rainfall patterns in both approaches, we present maps illustrating differences, in averaged thermal and dynamic fields, between the K3 and K4 frameworks. In addition to the 500 hPa geopotential height which has been used to define the WRs, the dynamical variables used also include the mean sea level pressure and the 500 hPa wind vector. The 850 hPa temperature field is used to characterize the thermal structure of each considered WR. The relative humidity field at the 850 hPa level is used to examine air moisture which is highly coupled to precipitation. For each WR, the average is computed using all days in the dataset associated with that regime, excluding neutral days. Figure 6 displays the differences for the AR and BLK regimes, while Figure S2 exhibits the differences for the NAO- regime. As shown in Figure S2, there are no notable differences in thermal and dynamic fields of the NAO- regime between the K3 and K4 approaches, in agreement with the similar Z500 anomalies and precipitation composites shown in Figs. 2, 3, 4, 5.

In contrast, the AR and BLK regimes display some notable thermal and dynamical differences between the K3 and K4 frameworks. These differences are most pronounced for the BLK regime, in agreement with the larger difference in rainfall anomalies but they are also evident for AR (c.f. Fig. 6). In both regimes, shifts in the anticyclonic centers of action explain the differences. In the case of AR, the ridge is shifted southeast towards Morocco in the K3 framework. As a result, there is an associated increase in north African Z500 (around 3 dam), and T850 (up to 1 degree). Furthermore, the 500 hPa wind slows (by up to 4 m/s) and RH850 drops (up to 6%) over Morocco. Although relatively modest, these differences are consistent with the stronger dry anomalies seen in the K3 AR regime. In the case of BLK, the K4 block is cut off from the subtropics producing weak cyclonic conditions over Morocco, whereas the K3 block is latitudinally extended with weak anticyclonic circulation over Morocco. This results in reduced humidity and lower westerlies in the K3 block.

4 Skills of Regime-Based Wintertime Rainfall Reconstructions

Having analysed the mean rainfall footprint of regimes in Morocco and their dynamical drivers, we now investigate their usefulness in representing the interannual variability in wintertime rainfall. Concretely, we analyse the skill of regime-based winter rainfall reconstructions at each of the 27 weather stations, for each regime framework. An assumption of this reconstruction is that the rainfall composites shown in Figs. 3, 4, 5 are near-stationary over this study period. We believe this is well justified due to the

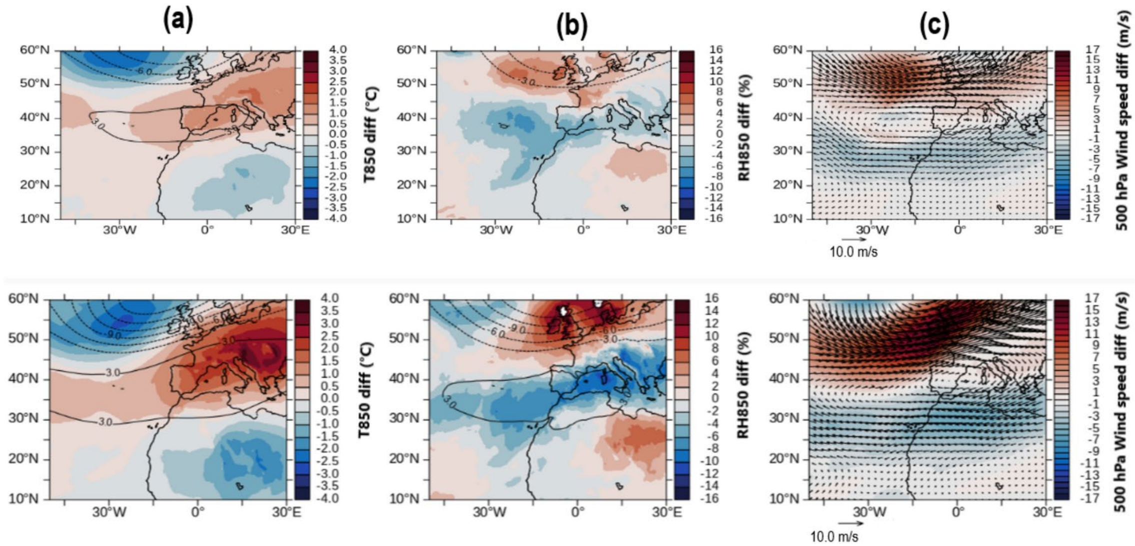

Fig. 6 Composites of differences between the K3 and K4 averaged fields overall **AR days** (top), and overall **BLK days** (bottom). For each WR, fields from the K4 framework are subtracted from the same fields of the K3 framework. WRs are computed using the full dataset, excluding neutral days. Differences are shown for **(a)** Temperatures at 850 hPa (shading) and geopotential height at 500 hPa (contours; units: dam). **(b)** Relative humidity at 850 hPa (shading; units: %) and mean sea level pressure (contours; units: hPa). **(c)** Wind speed at 500 hPa (shading; units: m/s) and wind vectors at 500 hPa (arrows). The blue and red color shading represent negative and positive anomalies, respectively

small changes in Euro-Atlantic circulation in the observational record. Further, we shall see post-hoc in Fig. 9, that there are no clear variations in reconstruction quality over the study period, which is evidence for stationarity. We compare the observed wintertime rainfall with the corresponding regime estimates generated from the K3, K4, and K7 frameworks, using two metrics: 1) Correlations between observations and regime-based reconstructions, as presented in Fig. 7 for the MR and WDF indices, and in Figure S3 for the EWDF index. 2) Normalized Root Mean Square Errors (NRMSE), as shown in Fig. 8 for the three indices. By normalizing the root mean square errors by the standard deviation of the observations, we ensure a fair comparison among different stations. This approach prevents over-interpretation of the regime construction's usefulness, especially in scenarios with low rainfall totals. It is important to note that neutral days were included in the regime-based reconstruction results presented in Figs. 7, 8, and 9 for all frameworks; however, they were treated as a separate category in the K3 and K4 frameworks, as explained in *subsection 3.1.*

The NRMSE is calculated as follows:

$$NRMSE = \frac{RMSE}{\sigma_O} = \frac{\sqrt{\frac{\sum_{y=1}^{N}(R_y - O_y)^2}{N}}}{\sqrt{\frac{\sum_{y=1}^{N}(O_y - \underline{O})^2}{N}}}$$

where: $RMSE$ is the root mean square error, σ_o is the standard deviation of the observations, O_y and R_y are respectively the seasonal rainfall observation and the seasonal rainfall reconstruction at year *y*, $\underline{O}$ is the average of seasonal rainfall observations over the whole studied period, N is the total number of years in the period.

The highest and statistically significant correlations at the 95% confidence level, alongside the lowest NRMSE values, are observed in Region I for all indices. However, Midelt and El Houceima present two particular stations with the lowest correlations and highest NRMSE in this Region for all indices. While their correlations are significant for the WDF and EWDF indices across all frameworks, the MR index shows significant correlations only for the K3 framework at El Houceima and for the K4 framework at Midelt. The particularity of El Houceima station can be attributed to its geographical location on the northeastern periphery of Region I, akin to Oujda station in Region II. Specifically, El Houceima's rainfall is influenced by the Mediterranean cyclones, and by a trough centered over the Iberian Peninsula, as shown in Figure S5. This trough isn't contained within the regime patterns, as it doesn't happen very often.

Similarly, Midelt is located on the periphery of Region I, close to Region III. Its position in the lee of the Middle Atlas Mountains creates a rain shadow limiting Atlantic influences on this location and heightening continental effects. El Hamly et al. (1997) actually put these two stations in distinct climatic regions. Furthermore, Fig. 7 highlights that the simpler K3 framework slightly outperforms the K4 framework in Region I for all indices. Specifically, averaged explained variance in the K3 framework reveals that WRs

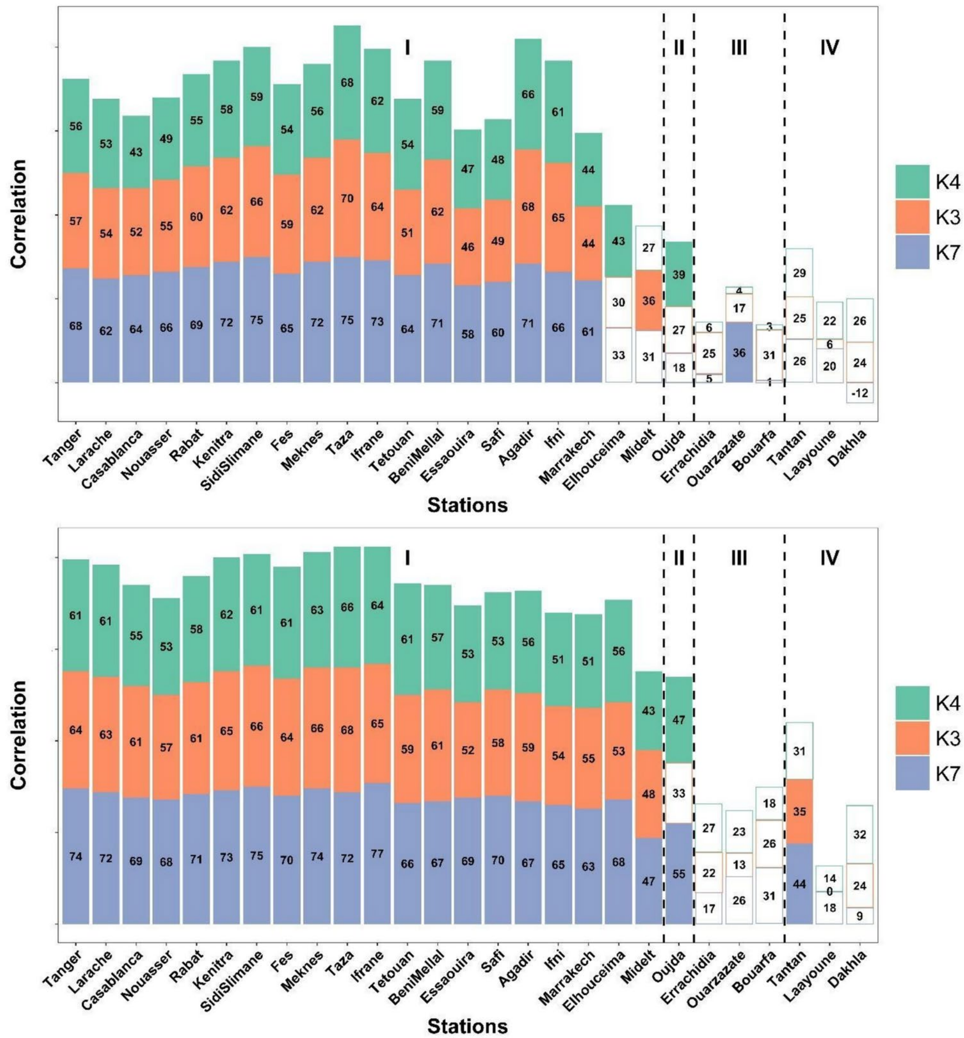

Fig. 7 Correlations (times 100) of mean rainfall (top) and wet days fraction (bottom) between observations and regime-based reconstructions, clustered per climatic Region. The full bars indicate statistical significance at the 95% level. The empty bars show non-significant correlations. Refer to supplementary material (Fig. S3) for the corresponding figure illustrating the fraction of extreme wet days

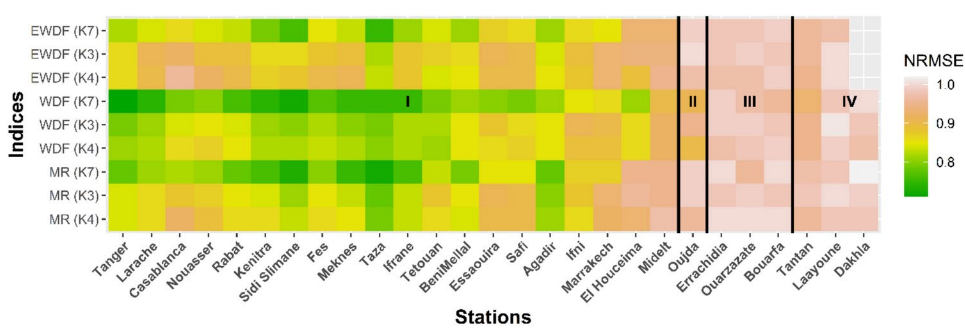

Fig. 8 Normalized Root Mean Square Error for the winter mean rainfall, wet days fraction, and extreme wet days fraction indices calculated using the K3, k4, and K7 frameworks, compared to the observed values

account for 33% of MR variance, 38% of WDF variance, and 28% of EWDF variance, compared to 30%, 35%, and 25%, respectively, in the K4 framework. These percentages rise to 46% for MR, 51% for WDF, and 36% for EWDF indices when using the more detailed K7 framework. Such relatively low percentages confirm the influence of factors, other than the North Atlantic regimes, on the precipitation variability, especially in Midelt and El Houceima stations which show low explained variances (13% and 9% respectively for the MR index and K3 framework).

In Region II, the K4 framework appears to impact rainfall patterns to some extent; correlations are statistically significant, albeit weak, for the MR and WDF (Fig. 7) indices. However, they are weak and statistically insignificant in the K3 approach. The fact that the K4 AR regime structure better captures meteorological flows generating humid conditions over the northeastern region of Morocco is probably due to the inclusion of the NAO+pattern, which projects strongly onto rainfall in this Region and generally represents widespread dry anomalies. As shown in Table 2,

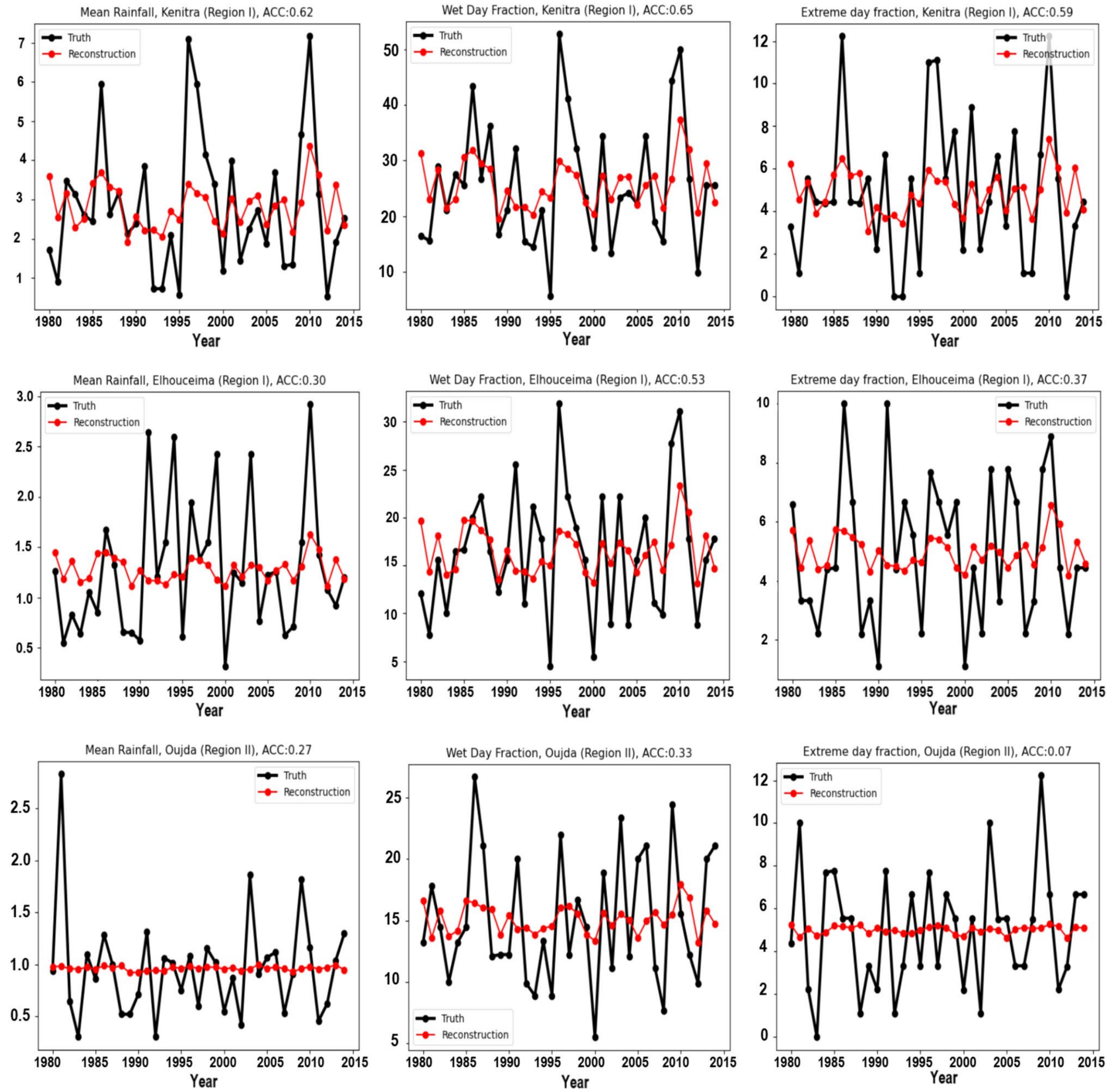

Fig. 9 Winter MR in mm/day (left), WDF in % (middle), and EWDF in % (right) at Kenitra (top) and El Houceima (middle) from Region I, and Oujda (bottom) from Region II. The black line is observations, the red line is regime-based reconstructions using the K3 framework. The ACC value corresponds to the correlation coefficient between the observed (truth) and the reconstructed rainfall time series

Table 2 Contribution of each WR (in %) to the fractions of wet days and extreme wet days, and to the total amount of precipitation (PRCPTOT) in Region II, using the k4 and k3 frameworks

		NAO+	NAO−	AR	BLK	No-regime
K3	WDF	/	22%	10%	20%	48%
	EWDF	/	18%	11%	21%	50%
	PRCPTOT	/	17%	15%	18%	50%
K4	WDF	12%	21%	15%	21%	31%
	EWDF	16%	17%	16%	20%	32%
	PRCPTOT	14%	16%	19%	18%	33%

while the contributions of the NAO- and BLK regimes in Region II to the total precipitation and the fractions of wet and extreme wet days are quite similar in both approaches, the K4 AR regime is associated with an increase in precipitation, compared to the K3 AR regime (contribution of 19% versus 15% to the total precipitation). Interestingly errors in regime-reconstructed rainfall are not symmetric: from examining a small number of stations in Region I, we find that NRMSE for the driest 14 winter seasons (MR < 40th percentile) is double that of the wettest 14 seasons (MR > 60th percentile; not shown), in both K3 and K4 frameworks. This indicates regimes tend to overestimate the amount of rainfall in dry seasons but handle extremely wet seasons comparatively well. This can be understood by seeing that the NAO- regime has strong positive rainfall signals in Region I, whereas negative signals in the other regimes are in general weaker. That is, very wet winters are typically heavily influenced by the Euro-Atlantic regimes, while the drier winters are not. The moist westerly flow is blocked by the Rif, the High Atlas and the Middle Atlas, and reaches Region II from the south after circumventing the Mountains, modulating to some extent rainfall variability there. Moist air from western Mediterranean perturbations emerges, as will be shown hereafter, as an important factor of rainfall variability (Baldi et al. 2004; Martin-Vide and Lopez-Bustins 2006; Xoplaki et al. 2012).

In Regions III and IV, correlations between the truth and the reconstructions are mostly weak and statistically not significant across all indices and frameworks. High NRMSE values are also observed in these Regions regardless of the framework. Furthermore, the MR explained variance in Regions II, III, and IV drops drastically to approximately 5% in the K3 framework. All the above results underscore the limited impact of North Atlantic WRs on rainfall when targeting those Regions, and support previous studies indicating similar results (Balhane et al. 2024; Born et al. 2010; Driouech et al. 2010a). Several factors contribute to these findings. First, Regions III and IV are located at the periphery of the North Atlantic's direct influence, where the impact of North-Atlantic dynamics tends to diminish. Furthermore, Morocco's mountain ranges, which cover nearly a third of the country, act as a significant barrier to the North Atlantic weather systems, and can significantly modify the influence of WRs in these Regions. As moist air masses encounter the mountains, they are forced to rise, cooling and leading to precipitation on the windward side (northwestern Morocco), while creating a rain shadow effect on the leeward side (southern Morocco), which could explain the reduced rainfall in Regions III and IV. These changes may, in turn, feed back into large-scale circulation patterns, potentially affecting the structure and persistence of the WRs.

A closer examination of the more detailed K7 framework shows that it performs well in Region I, enhancing the match between actual measurements and regime-based estimates for all indices (Fig. 7). In contrast, it does not provide any important added value in Regions III and IV where the correlations are weak and statistically not significant. In Region II, increasing the number of weather regimes to seven yields higher and significant correlations, although only for the WDF index (as shown in Figure S3). This complex framework offers, through additional patterns, more qualitative details about rainfall patterns that are not captured by the simpler K3 framework, allowing for a better understanding of the relationships between WRs and the WDF index within this Region.

Figure 9 presents rainfall reconstruction skills, using the K3 framework, at three stations, Kenitra and El Houceima in Region I, and Oujda in Region II. The choice of Kenitra station is motivated by its coastal position on the Atlantic Ocean, exhibiting high correlations between observations and reconstructions for all frameworks, along with low NRMSE values. In contrast, the selection of El Houceima is driven by its geographical position on the Mediterranean coast, bordering Region II and exhibiting low correlations between the observations and the reconstructions compared to the average in Region I. The focus on Regions I and II is justified by their higher susceptibility to the influence of North Atlantic WRs, compared to Regions III and IV. The rainfall reconstructions correctly reflect the observed variability for the three indices in Kenitra and El Houceima, despite differences in the amplitudes; this feature is observed in all stations in Region I. For instance, the three prominent peaks in Kenitra's observed data for the winters of 1986, 1996, and 2010 find a parallel qualitative representation in the three highest peaks of the reconstructions, although a rough ratio of about 2 between observations and reconstructions amplitudes. For the Northeastern station Oujda, Fig. 9 underscores the challenges in reconstructing observations, especially for the quantitative MR and EWDF indices. The reconstructed time series are excessively flat. These findings align with the coefficient of variation (CV) calculated, to assess the inter-annual variability, as the ratio of the standard deviation to the mean of precipitation for the observations and reconstructions datasets respectively (Table S4). It consistently exhibits higher values for the observation datasets compared to the reconstructions across all indices, confirming that the regime-based reconstruction method provides a smoothed representation that underestimates the interannual variability of rainfall indices. For instance, at Kenitra, the CV of the reconstructions represents approximately one-third of the CV of the observation for all indices. Moving to Oujda, the CV of the reconstructions represents only a small fraction of the observed interannual variability (4%

for MR, 21% for WDF, and 7% for EWDF) of the observed CV. This also confirms that the regime-based reconstruction method captures more rainfall variability in Region I than in Region II (Table S4 shows the averaged CV over each of the Regions).

Focusing on the winter peaks of 1996 and 2010 in Kenitra and El Houceima stations, Table 3 compares the WRs frequencies calculated over all winters of the studied period, and for each of these very wet winters. For instance, the winter of 2010 recorded a rainfall accumulation of approximately 120% and 85% the annual mean calculated over the 1979–2014 period at Kenitra and El Houceima respectively. They were marked by a high frequency of the negative phase of the NAO, especially during the winter of 2010. In the K3 framework, the frequency of NAO- reached 30% during the 1996 winter and an extraordinary 66% in the 2010 winter, which contrasts sharply with its 17% average frequency over the 34 winters. The winter of 2010 showed a high persistence of the NAO- regime (Cattiaux et al. 2010; Seager et al. 2010; Wang et al. 2010), which commonly caused a displacement of the mid-to high-troposphere flows to more southern latitudes (Barriopedro et al. 2006; Seager et al. 2010), generating extreme winter precipitation in the Iberian Peninsula and northern Africa. Simultaneously, the positive phase of the NAO, associated with generalized dry conditions over Morocco, was almost absent in the K4 approach (0% in the 1996 winter, and 2% in the 2010 winter), compared to the average of 23%. Furthermore, the frequencies of the AR and BLK regimes have dropped considerably during both winters compared to their averages over the whole period. Blocking regimes act as a blocking mechanism preventing the west-to-east transport of moist air masses from the Atlantic Ocean (Kautz et al. 2022; Steinfeld and Pfahl 2019).

The winter of 1981, which was exceptionally humid in Region II, saw a rainfall accumulation of 255 mm at Oujda station, nearly 100% of the annual mean calculated over the 1979–2014 period. This winter was characterized by a predominant AR regime (c.f. Table 3), which occurred with a frequency of 41% in the K3 framework—well above its 15% average frequency. On these AR days, rainfall accumulation reached 163.5 mm, accounting for 64% of the 1981 winter total amount. Only five AR days during this winter recorded 158 mm of rainfall. By focusing on extreme wet days (days with rainfall exceeding the 95th percentile) within the full dataset, we find that 19% of extreme wet days belong to the AR regime. They contributed to 27% of the cumulative extreme rainfall, further emphasizing the extreme nature of this regime in Region II. It is worth noting that contrary to Oujda, the 1981 winter was dry in Kenitra and Region I in general. This is consistent with the Rainfall-WRs link shown in Fig. 3; AR is associated with drier conditions in Region I, especially for the K3 framework. Additionally, the "no-regime" category was significantly represented in both approaches during the 1981 winter, accounting for 43% of the frequency and a rainfall accumulation of 75.6 mm, which is 28% of this season's total amount. The frequency of neutral extreme wet days in the whole dataset rises to 50%, contributing to 49% of the cumulative extreme rainfall. This indicates a prevalence of weather patterns that do not fit within the defined North Atlantic weather regimes, such as systems coming through the Mediterranean. Figure 10 illustrates the impact of western Mediterranean weather patterns on the Northeastern region of Morocco. Synoptic fields averaged over all extreme wet days in Region II reveal a typical meteorological circulation pattern characterized by a low-pressure system located to the west of the Mediterranean basin, coupled with a pronounced thermal gradient at the 500 hPa level. Local forecasters refer to this atmospheric configuration as "retour d'est" (literally "return from the east" in English) due to the movement of moist air masses eastward over the Mediterranean Sea, followed by a westward turn. This circulation pattern results in the advection of moist and cold air in a Northeast-Southwest axis along the western Mediterranean coastline, including Region II. This "retour d'est" phenomenon is of significant interest for weather forecasts for this region due to its potential to generate substantial extreme weather conditions, impacting areas along the western Mediterranean coastline.

This section highlights the robust performance of the K3 framework, which rivals that of the K4 framework in Region I. In contrast, the performance in the remaining regions is characterized by modest correlations across all frameworks, indicating limited influence of North Atlantic WRs. In those Regions, Mediterranean perturbations and subtropical dynamics play more significant roles in shaping rainfall variability and are outside the scope of this work (Knippertz et al. 2003). While the extended K7 framework provides valuable insights into seasonal rainfall patterns in Region I, it does not serve to increase skill in other regions.

Table 3 Weather regime frequencies in the K3 and K4 frameworks during the winters of 1981, 1996, 2010, and on average over the full period

	NAO+		NAO-		AR		BLK		No-regime	
	K3	K4	K3	K4	K3	K4	K3	K4	K3	K4
All winters	×	23%	17%	16%	15%	14%	21%	17%	47%	30%
1981 winter		9%	9%	4,5%	41%	33%	7%	10%	43%	43%
1996 winter		0%	30%	28%	11%	12%	10%	28%	49%	32%
2010 winter		2%	66%	65,5%	5%	3%	10%	15,5%	19%	14%

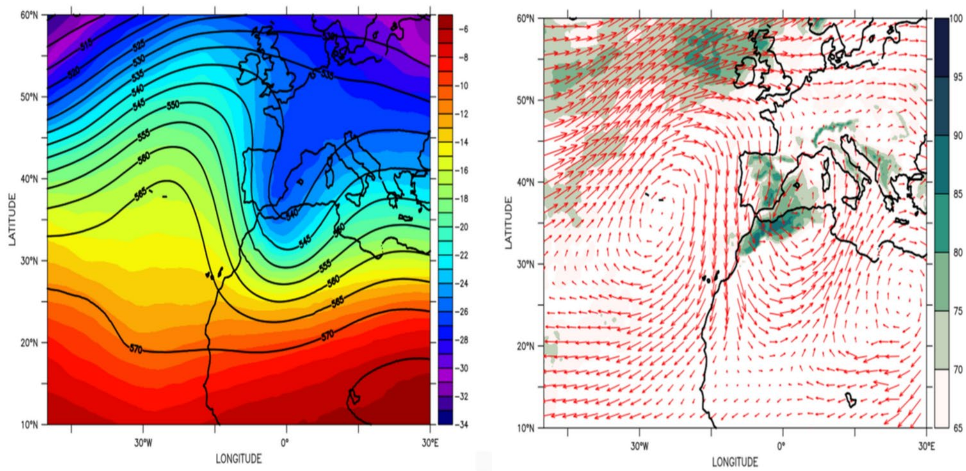

Fig. 10 Averaged fields overall extreme wet days in Region II, for (**left**) Temperatures at 500 hPa (shading; units: °C) and geopotential height at 500 hPa (contours; units: dam), (**right**) Relative humidity at 850 hPa (shading; units: %) and wind vectors at 850 hPa. Colored areas in the right panel (relative humidity > 65%) show where moisture is likely to be available for cloud development

Focusing on extremely wet seasons in Regions I and II, it has been shown that WRs contribute differently to total rainfall. While the AR regime is in general associated with drier conditions in Region I, it contributes significantly to extreme rainfall in Region II during the 1981 winter. Conversely, while the NAO- contributed significantly to extreme precipitation during the winters of 1996 and 2010 in Region I, its impact on Region II was not significant. These findings underscore the nuanced relationship between WRs and rainfall patterns across different regions of Morocco, highlighting the complexity of rainfall variability in Morocco.

5 Discussion

This study investigates the role of weather regimes (WRs) in explaining Morocco's wintertime rainfall variability, with a focus on comparing two distinct WR frameworks: geopotential-jet regimes (Dorrington and Strommen 2020), and the classical four regimes (Michelangeli et al. 1995). While the classical four WRs represent a widely recognized framework in atmospheric science, the geopotential-jet regimes have been previously shown to be more numerically stable, and so particularly suited for understanding a changing climate (Dorrington et al. 2022a). Using observational data from a set of meteorological stations, we explore the link between WRs and Moroccan winter rainfall, encompassing both average and extreme rainfall events. We also highlight the dynamic and thermo-dynamic differences and similarities between WRs in the two frameworks. Through this investigation, we aimed to assess for the first time the potential of geopotential-jet regimes as a useful tool for understanding and predicting Moroccan rainfall characteristics, summarized in our following conclusions. In this section, we discuss the impacts of methodological choices and the limitations of the WR framework in understanding wintertime rainfall variability in some parts of Morocco.

By purposefully removing the variability in jet speed, geopotential-jet regimes tend to exclude the steady zonal NAO + flow from the regime classification. While the classical approach associates this regime with anticyclonic and dry weather over Morocco, its absence in the GJRs framework appears to have no significant impact on the ability to reproduce Moroccan rainfall variability from regimes. NAO + patterns are mainly integrated into the blocking regime in the GJR approach, and somewhat into the Atlantic Ridge regime. This results in different impacts of these two WRs on Moroccan weather, depending on the used approach (see Figs. 3,4,5).

Furthermore, the introduction of a "neutral" category, to distinguish days not strongly aligned with any regime, does not help in explaining rainfall variability in the Moroccan regions most influenced by North Atlantic WRs, regardless of the number of regimes considered (c.f. Fig. S1). Consequently, the addition of a "neutral" class was deemed unnecessary, as it involves additional ad-hoc parameter choices. Instead, good results are obtained when conducting the rainfall analysis using all available data, including neutral days. This is likely because this category consists of days lacking a clear driving influence, failing to present a coherent signal that can be directly linked to specific rainfall outcomes.

The contribution of the NAO- regime to the Moroccan rainfall patterns remains distinctive and invariant in both classical and GJR approaches. This regime is associated with humid conditions in Morocco. Notably, its frequency of occurrence serves as a skillful predictor of winter rainfall in Morocco, in particular in the humid, northwestern part of Morocco. The analysis of the dynamic and thermal fields associated with WRs shows similar NAO- dynamics in both regime frameworks. In contrast, the AR and BLK regimes exhibit differences in dynamic and thermal fields in both approaches. In the GJR approach, the BLK regime and, to a lesser extent, the AR regime are more dominated by the anticyclonic anomaly compared to their classical counterparts, particularly over North Africa. Under the AR regime, the ridge in the GJR framework shifts southeast towards Morocco, fostering anticyclonic conditions over Morocco. In the case of the BLK regime, the classical blocking system is cut off from the subtropics, resulting in weak cyclonic conditions. Meanwhile, the GJR blocking system extends latitudinally, yielding weak anticyclonic circulation and decreased humidity.

Outside of the north and north-west of Morocco however, low correlations between observed rainfall and regime-based reconstructions suggest a limited impact of North Atlantic WRs. Systematically quantifying the drivers of rainfall in the subtropical regions of Morocco, as we have aimed to do here with regimes in the higher latitudes, represents a fascinating area of future research. Rainfall in southern Moroccan regions has been linked instead to tropical-extratropical interactions through smaller-scale synoptic weather systems, such as cut-off lows and upper tropospheric troughs. Warm, moist air from the tropics, associated with atmospheric rivers or tropical moisture plumes extending into Morocco, impacts Regions III and IV (Fink and Knippertz 2003; Knippertz and Martin 2005; Khouakhi et al. 2022). Additionally, precipitation in southern Morocco may also be influenced by continental moisture originating over the Sahel (Fink and Knippertz 2003; Knippertz and Martin 2005), transported by tropical easterly waves (De Vries 2020). Further, local processes such as orographic lifting, convection and coastal interactions significantly impact the climate in the studied Regions. A good knowledge of these local processes can improve our understanding of rainfall variability over Morocco, helping to address the gaps in the current weather regime-based approach. For example, when sufficient moisture is available, orography can create localized weather patterns through the foehn effect, leading to enhanced rainfall at the western slopes of the mountains (Region I). Orographic lifting along the southern slopes of the Atlas Mountains can also trigger convective precipitation in Region III (Knippertz et al. 2003; Chaqdid et al. 2023). Additionally, in these southern Regions, the proximity to the Sahara Desert can significantly influence local weather patterns, particularly through thermal circulations. The hot and dry Chergui wind can sweep across Morocco from the southeast, affecting temperature and moisture levels in these regions. This eastern wind can contribute to drying out the atmosphere, inhibiting cloud formation, and reducing the likelihood of rainfall. However, in some conditions, the interaction between the Chergui and incoming moist air from the Atlantic can create strong local convergence zones, leading to significant localized convective rainfall.

Understanding how North Atlantic WRs interact with local processes and other large-scale factors such as subtropical dynamics is also essential to better grasp the complexity of rainfall variability, particularly in southern Regions. Cut-off lows in subtropical regions can interact with WRs to intensify localized convection in Regions III and IV, leading to intense rainfall events. Both regions experience more frequent tropical-extratropical interactions when the mid-latitude jet is shifted polewards (Chaqdid et al. 2023). A drying effect of El Niño -Southern Oscillation (ENSO) on precipitation in North-West Africa has been reported in different studies (e.g., Nicholson and Kim 1997; Ward et al. 1999; Mariotti et al. 2002; Knippertz et al. 2003; Driouech et al. 2010b; Donat et al. 2014). Driouech et al. 2020b noted that some years or periods with rainfall deficit were marked by at least one strong ENSO event. The Madden–Julian Oscillation (MJO) was also reported to contribute to rainfall variability in Morocco and North Africa through its effect on midlatitude atmospheric circulations that modulate WRs (Gadouali et al. 2020; Schreck III 2021; Chaqdid et al. 2023). However, these aspects require specific investigations which are beyond the scope of the present study.

It is worth noticing that this study focused on Morocco, shows both similarities and differences compared to other areas influenced by North Atlantic WRs. Our results for northern Morocco are consistent with previous findings on the effect of WRs on Southern Europe and the Mediterranean (Cassou 2008; Gadouali et al. 2020; Santos et al. 2005). However, our findings also reveal the limited role of North Atlantic WRs in southern Morocco, highlighting the need for a region-specific approach. Such an approach should integrate large-scale North Atlantic WRs with finer-scale local features and subtropical dynamics to provide a more comprehensive understanding of rainfall variability in these regions.

6 Conclusion

Wintertime rainfall across Morocco is notably influenced by the large-scale circulation patterns in the North Atlantic domain. This study explores the relevance and applicability of North Atlantic weather regimes in modeling seasonal rainfall accumulations over Morocco. This is crucial for enhancing our understanding of climate projections, as direct rainfall predictions from climate models are severely flawed.

Previous studies have demonstrated the ineffectiveness, in the case of Moroccan winter precipitation, of such regime-based reconstructions for statistical downscaling of climate projections. These reconstructions employed four classical WRs derived from a K-means clustering algorithm on large-scale geopotential height anomalies at 500 hPa in the Empirical Orthogonal Functions phase space. (Dorrington and Strommen 2020) suggest that this ineffectiveness is at least in part due to instability in the classical regime patterns themselves, which confounds any potential changes in the regime-rainfall teleconnection itself. They proposed combining both jet and geopotential height data to obtain a more stable set of three regimes, or alternatively, a nearly-as-stable set of seven regimes for more detailed analysis. This hybrid approach filters out the linear variability of jet speed prior to clustering in order to focus on the impact of fundamentally nonlinear jet-latitude variations on the geopotential height field.

We envision that enhanced climate modeling techniques and more stable WRs could provide valuable insights into constraining future precipitation changes in Morocco. As an initial step toward this objective, this work leveraged observational data from 27 weather stations across Morocco to investigate the link between weather regimes and Moroccan winter rainfall through both statistical and dynamical lenses. We deliver a detailed investigation of regime influences on Moroccan rainfall. Our findings also outline a practical framework for integrating regime-based insights into precipitation trend analyses under future climate scenarios. The key results of this paper are summarized as follows:

- In the densely populated and economically vital northwest of Morocco (Region I), an important part of rainfall can be effectively modeled using weather regimes, regardless of the used approach, validating their application in future research. Conversely, in eastern and southern climatic Regions, weather regimes of any kind, prove ineffective, which may be attributed to the increased relevance of subtropical dynamics and trough structures falling outside the Euro-Atlantic domain, or to non-recurrent dynamic systems not contained in WRs patterns. Future research should pinpoint the pertinent low-latitude large-scale drivers affecting rainfall variability in the south and southeast parts of Morocco, which could then be analyzed within climate models.
- While correlations between actual and regime-reconstructed rainfall are relatively high in Region I, the absolute value of the rainfall is often far too low. This small-signal issue is to be expected when using large-scale dynamical regimes as a proxy for small-scale surface weather, and could plausibly be reduced by including additional variability modes, such as tropical wave activity, or by using extreme event precursor indices, as in (Dorrington et al. 2024). However, in the context of hydrometeorological climate analysis, having an accurate sense of the sign of local anomalies is a strong starting point, and we believe that when considering changes in climate (i.e. on multi-decadal timescales) the relevance of this small signal will be less than on the inter-annual scale considered here, as individual extreme synoptic events – unattributable to regimes – will be increasingly averaged out.
- Correlations between observed rainfall and regime-based reconstructed rainfall show the three geopotential-jet regimes are at least as effective as the four classical WRs. The K3 framework slightly outperforms the K4 framework in Region I by explaining 3% more variance across all indices, with one fewer regime pattern.
- The extension to seven patterns in the geopotential-jet framework improves rainfall reconstructions in Region I, but only marginally and so not justifying, in our view, the additional analytical complexity involved.
- While the K3 framework requires one additional computational step (jet speed filtering), making it slightly more complex to compute, it is simpler than K4 from an analytical perspective. The fewer patterns in K3 reduce sampling error and data dimensionality, leading to more straightforward interpretation and application, particularly in climate projections. Moreover, the demonstrated stability of the K3 regimes enhances their reliability and simplicity in climate analyses, making the study of trends and variability more accessible.

Therefore, to continue our research, we will focus on using GJRs to establish dynamical influences on future rainfall changes in Northwest Morocco, using CMIP6 ScenarioMIP data. The main assumption of such an approach is that the future regime-rainfall teleconnection will remain unchanged, allowing regimes to serve as a faithful proxy. Such an assumption has historically not been easy to validate, except with climate model rainfall projections – the uncertainties which motivate a regime-proxy approach in the first place. However, with the advent of kilometer-scale global climate simulations, we hope to be now able to validate this assumption to some degree, while then leveraging the comparatively well-resolved large-scale regimes in CMIP6 to explore the full range of climate scenario uncertainty.

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Author contributions Rachida El Ouaraini, Fatima Driouech and Joshua Dorrington designed the study, prepared the material and analyzed the results. Joshua Dorrington provided the script for computing classical and geopotential-jet regimes, as well as for regime-based reconstructions. Mohammad El Aabaribaoune contributed to script preparation. The initial draft of the manuscript was written by Rachida

El Ouaraini and Fatima Driouech. All authors participated in the improvement of the manuscript and approved the final version.

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Data availability Observed data is available at the General Meteorological Directorate. ERA5 data may be dowloaded from copernicus web site: https://cds.climate.copernicus.eu/datasets

Declarations

Competing interests On behalf of all authors, the corresponding author states that there is no conflict of interest.

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