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Predictability of cyclones associated with heavy precipitation events in the Sahara

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Abstract. Heavy precipitation events (HPEs) are a precious source of water in the Sahara, but often trigger devastating flooding. These events are strongly associated with surface cyclones, making accurate cyclone forecasting crucial for predicting hazards related to HPEs and their impacts. In this study, we investigate the predictability of HPE-associated cyclones across the Sahara and its drivers. We use ERA5 reanalysis and ECMWF initialized reforecasts between December 2000 and November 2020. Forecast skill on short-, medium-, and extended-range timescales is evaluated based on the overlapping areas of observed and forecasted cyclones over the Sahara. Results show that the lead time of skillful prediction is up to about 10 days. In winter, when cyclones are mainly located in the northern Sahara, forecast skill is higher for deeper cyclones. In summer, skill is higher for cyclones located in the southwestern Sahara. On short-range lead times, forecast skill is higher in winter, whereas on medium to extended lead times, skill is higher in summer and fall. Rossby wave patterns extending over the North Atlantic are associated with both high and low skill forecasts, highlighting a flow-dependent control on predictability over the Sahara and underscoring the need for more detailed investigation. These findings identify key controls and characteristics of skillful forecasts of cyclones that lead to HPEs in the Sahara on timescales of a few days to two weeks in advance. Understanding these variations across regions and seasons is key to improving the predictability of HPEs and their related impacts.

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1 Introduction

The Sahara is the largest warm desert in the world (Tucker et al., 1991). Most of the Sahara is hyper-arid (Middleton and Thomas, 1992), and it probably contains the driest region on Earth (Kelley, 2014). Yet, heavy precipitation events (HPEs) are actually quite common in the Sahara – occurring on average every other day (Armon et al., 2024), and often trigger flash floods (e.g., Fink and Knippertz, 2003; Schepanski et al., 2012; Yin et al., 2023), some of them highly destructive (Moawad et al., 2016; Armon et al., 2025). Rainfall water is also a valuable resource in the Sahara, with as little as a few mm already making significant recharge of groundwater or even surface reservoirs (e.g., Cuthbert et al., 2019; Rieder et al., 2025). Precipitation forecast, fundamental in reducing risks from floods and managing water resources in real time is constantly improving, but has much worse skill over deserts (e.g., Kalma and Franks, 2003; Rinat et al., 2021; Cordeira et al., 2025), where the combination of sparse observations, small-scale precipitation generation processes and short-duration storms (e.g., Sharon, 1972; Belachsen et al., 2017) pose a major predictability challenge.

Despite these challenges, heavy precipitation in the Sahara, particularly, though not exclusively, in its northern half and during winter, is often associated with surface cyclones (Fig. 1; Nicholson, 1981; Morin et al., 2020; Armon et al., 2024). This link suggests, therefore, that forecasting cyclones may provide an indirect but powerful pathway to improving desert rainfall predictions. Understanding cyclone predictability in and near the Sahara is therefore key in improving precipitation forecasting, ultimately enabling better preparedness for desert flood hazards and water resource management. As numerical weather models are inherently limited by uncertainties in initial conditions and unresolved physics (Mason, 1986; Slingo and Palmer, 2011), forecast skill is often evaluated across an ensemble of forecasts, produced by perturbing their initial conditions (Leutbecher and Palmer, 2008; Palmer, 2017). However, when examining cyclone predictability across the North Atlantic and its surroundings, Afargan-Gerstman et al. (2024) showed that cyclones over the Sahara exhibit negative biases on the order of magnitude of the cyclone climatology, suggesting that the dynamics of cyclones over this region and their impacts are not well represented by the forecast model.

Cyclones in the Sahara originate through different dynamical processes that vary regionally and seasonally. The northwestern Sahara experiences peak precipitation in the fall, when extratropical cyclones migrate southward over the eastern North Atlantic, drawing moisture from tropical latitudes to the desert (e.g., Skinner and Poulsen, 2016; Chaqdid et al., 2023) and advecting Atlantic moisture around the Atlas Mountains (Rieder et al., 2025). In the northeastern Sahara, HPEs are much rarer and occur sporadically, mostly outside the summer months (Morin et al., 2020). They are mainly associated with Mediterranean cyclones (e.g., Ammar et al., 2014; Armon et al., 2025; Flaounas et al., 2025) or indirectly with Tropical Plumes that form when mid-latitude cyclones intrude southward, passing through the Mediterranean towards the Sahara (e.g., Rubin et al., 2007; Armon et al., 2018). Occasionally, the active Red Sea trough, often enclosing a surface cyclone (Ziv et al., 2022), can also produce rainfall in the region (De Vries et al., 2013). In the southern Sahara, HPEs occur mostly in summer, when the tropical monsoon belt extends northward. Shallow monsoon lows, sometimes invigorated by African easterly waves, emerging from the Sahel are a major source for precipitation (Nicholson, 2000; Russell and Aiyyer, 2020). In addition, more stationary, thermally driven systems such as the Saharan heat low (Lavaysse et al., 2009; Engelstaedter et al., 2015) and the Sudan monsoon

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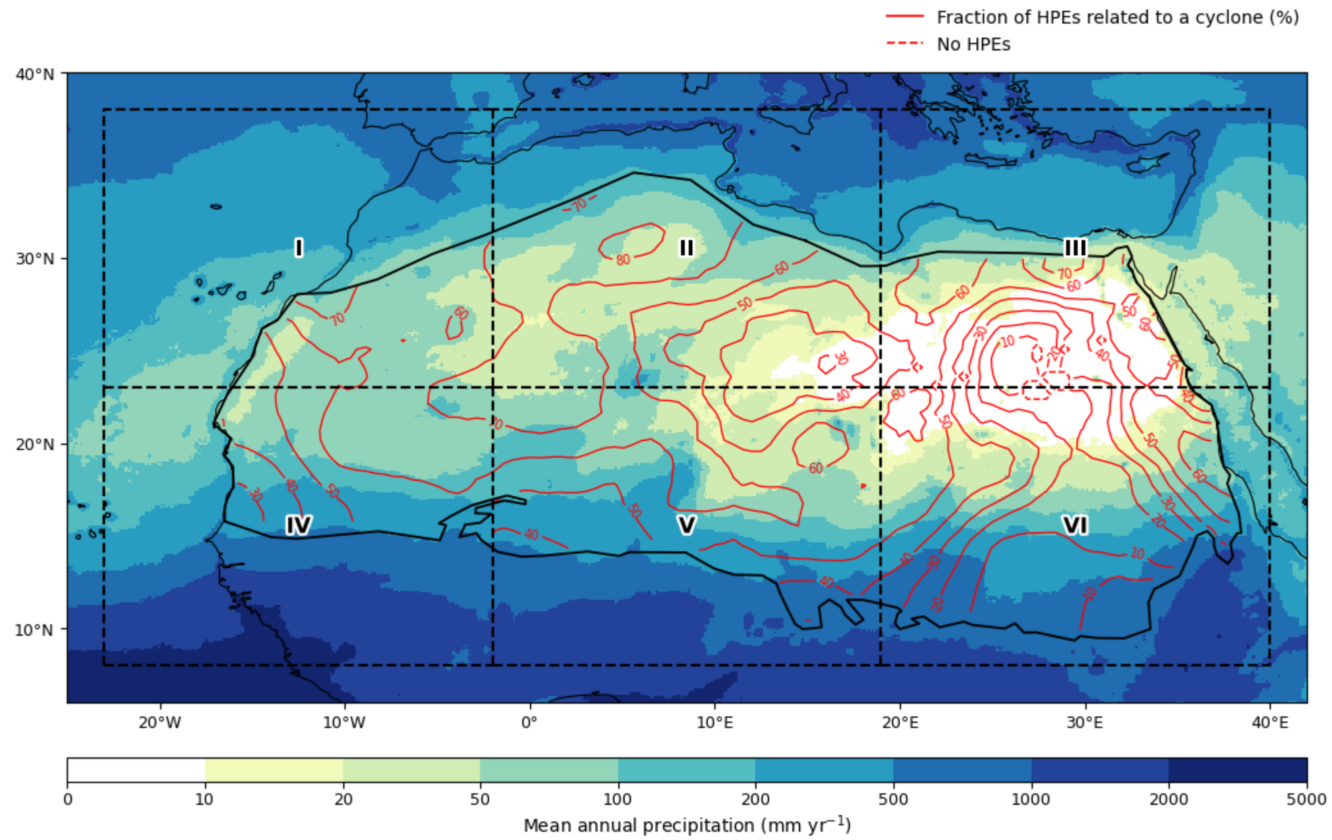

Figure 1. Mean annual precipitation (colors) and the fraction of HPEs associated to a cyclone compared to all HPEs. Precipitation is from satellite-based data, and HPEs and their association with cyclones are based on Armon et al. (2024) (Sect. 2.1.1). The thick black solid line represents the boundary of the Sahara (Kelso and Patterson, 2010), while the outer black dashed lines indicate the study region, which is divided into six subregions (I–VI).

low (El-Fandy, 1948) normally dry on their poleward side cantrigger convection along their equatorward flanks, occasionally generating rainfall that propagates northward (e.g., Peyrillé et al., 2007).

As surface cyclones are synoptic-scale systems embedded in the large-scale flow, it may be expected that cyclones exhibit a certain level of predictability that can be inherited from the background circulation. At short lead times, numerical weather prediction models indeed provide skillful forecasts of individual cyclones, typically up to a few days (Froude, 2009; Zheng et al., 2019; Ngoungue Langue et al., 2021; Elless, 2018; Li et al., 2016). Beyond this range, however, forecast errors grow rapidly and predictability decreases, partly due to the amplification and downstream propagation of errors within the large-scale flow.

Persistent circulation regimes and teleconnection patterns can give rise to enhanced predictability on subseasonal to seasonal (S2S) timescales (Domeisen et al., 2022). These patterns, such as the North Atlantic Oscillation (NAO), the East Atlantic

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(EA) pattern, the Madden–Julian Oscillation (MJO) (e.g., Stan et al., 2022), and variability in the stratospheric polar vortex, modulate cyclone activity and thus provide potential sources of extended-range S2S predictability (Zheng et al., 2019; Black et al., 2017; Afargan-Gerstman et al., 2024; Rupp et al., 2024). Additionally, synoptic weather systems are often embedded in mid-tropospheric Rossby waves along the jet stream (Wirth et al., 2018), and induce high-impact weather through coupling between the tropics and the extratropics (e.g., Martius et al., 2008; De Vries et al., 2013, 2024). This suggests that Rossby wave patterns and breaking act as potential precursors of high-impact cyclones in subtropical regions.

Despite, and perhaps because of the role of large-scale circulation in modulating cyclone activity, the ability of numerical models to exploit this predictability varies across flow regimes (e.g., Rodwell et al., 2018; Spaeth et al., 2024). Specifically, the predictability of Saharan cyclones remains poorly understood. An important question that therefore arises is how predictable are Saharan cyclones and which atmospheric conditions contribute to enhanced predictability of these cyclones. This study addresses this question by systematically assessing the forecast skill of HPE-associated Saharan cyclones and identifying the atmospheric factors linked to their predictability.

The paper is structured as follows. Sect. 2 describes the data and study region, and presents feature-oriented and magnitude-based methods for assessing Saharan cyclone forecast skill. The temporal and spatial variations in the forecast skill, and the association between large-scale weather patterns and the forecast skill for HPE-associated cyclones are presented in Sect. 3. Finally, Sect. 4 discusses the mechanisms governing cyclone predictability across Saharan regions and seasons, and points out directions for future research.

2 Data and methods

2.1 Data

To investigate the predictability of HPE-associated cyclones in the Sahara and the factors controlling it, we used three main datasets: (a) observed HPEs derived from the Integrated Multi-satellitE Retrievals for GPM (IMERG) precipitation dataset between 2000 and 2021 (Armon et al., 2024); (b) meteorological fields from the fifth generation ECMWF atmospheric reanalysis (ERA5) dataset, together with cyclone tracks identified by Sprenger et al. (2017) based on the same dataset; and (c) subseasonal reforecasts from ECMWF, covering 2000 to 2020. These datasets provide the observational, reanalysis, and forecast basis for the analyses presented in the following sections.

2.1.1 Saharan HPEs

We used a catalog of Saharan HPEs between June 2000 and May 2021 from Armon et al. (2024) to extract the cyclones matching the reforecast data period (Sect. 2.1.3). These events were identified and obtained using daily-aggregated precipitation from the IMERG Version 06. Events in this catalog were detected when rainfall exceeded the local 90th percentile of rainy days (daily rain > 1 mm). Neighboring threshold-exceeding grid cells were merged into continuous storm areas larger than 1000 km^2, and nearby events in space or time were connected. This approach captures only large, coherent rain systems and filters out

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isolated or noisy rainfall signals. From the nearly 42,000 HPEs in the catalog, we retained only around 12,500 cases in which cyclones were associated with HPEs, according to a Monte Carlo cyclone-association test performed in Armon et al. (2024) that determines whether HPEs occur closer to a cyclone than would be expected by chance, based on repeated comparisons with randomly selected cyclone dates. For each of those cyclone-associated HPEs, we extract the date of maximum precipitation volume, the precipitation mass center location, and the minimum distance to the nearest cyclone border.

2.1.2 ERA5 dataset and cyclone data

To characterize the meteorological conditions during HPE-associated cyclones, we used the ERA5 reanalysis dataset. Specifically, we used mean sea level pressure (MSLP), 500 hPa geopotential, which were converted into geopotential height (GH500), and 850 hPa temperature (T850) data, with a temporal resolution of 3 h at a 0.5° spatial resolution (Hersbach et al., 2020). To associate cyclones with the Saharan HPEs, we used surface cyclone data produced by Sprenger et al. (2017), who applied an objective cyclone detection and tracking algorithm (Wernli and Schwierz, 2006) based on MSLP, defining cyclones as enclosed regions containing one or more sea level pressure minima. For every cyclone, the algorithm yields a two-dimensional binary cyclone mask field.

2.1.3 Subseasonal reforecast data

To evaluate the predictability of HPE-associated cyclones in the Sahara, we use ECMWF ensemble reforecasts. These reforecasts were initialized between December 2000 and November 2020, with a 6-hour time interval and a 46-day forecast period from several model versions: CY47R1, CY47R2, and CY47R3. The reforecasts consist of 11 ensemble members initialized from ERA5 twice a week, on Monday and Thursday. These reforecasts are part of the S2S Prediction research project database, an ongoing research effort to improve forecast skill and understanding of the climate system on subseasonal to seasonal timescales (Vitart et al., 2017). The cyclone detection algorithm was applied to the 10 reforecast perturbed ensemble members (excluding the control run), providing a cyclone forecast which is verified against reanalysis data.

2.2 Methods

2.2.1 HPE-related cyclone identification

To associate cyclones with observed HPEs, the distance between the precipitation mass center of a given HPE and the location of the nearest cyclone center according to its minimum sea level pressure at 12 UTC on the date of maximum precipitation volume was calculated. This procedure was applied to determine the location of each HPE-associated cyclone. Cases where the detected cyclone is located at a distance $\geq$ 2000 km and/or outside the six subregions (Fig. 1) were discarded. An example of this approach, showing the association of the nearest cyclone with a HPE during 20–24 November 2024 is in Fig. A1. It is important to note that in our methodology, a single cyclone may be associated with more than one HPE. Nonetheless, when calculating average values (e.g., composites across events), every cyclone was counted only once. This approach ensures that

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Table 1. An example of a contingency table for verification of reforecasts. The value of each category for a verified case study is calculated based on the corresponding area within the cyclone-related study area.

Forecast/Observation	Observed	Not Observed
Forecast	Hits	False Alarms
Not Forecast	Misses	Correct Negatives

subsequent evaluations were not biased by multiple associations of the same cyclone. We then expanded the cyclone mask by six degrees (Fig. 2 and Fig. A1) to obtain an *ad-hoc study region* in which we evaluate forecasted cyclones (as explained next).

2.2.2 Forecast verification

Cyclone frequency in the reforecasts was verified against reanalysis using an area-based four-category contingency table (Table 1 and Fig. 2), applied separately to each ad-hoc study region. For every ensemble member and forecast lead time, the table was constructed by summing the area of the grid points that met each category in the table within the corresponding ad-hoc study region.

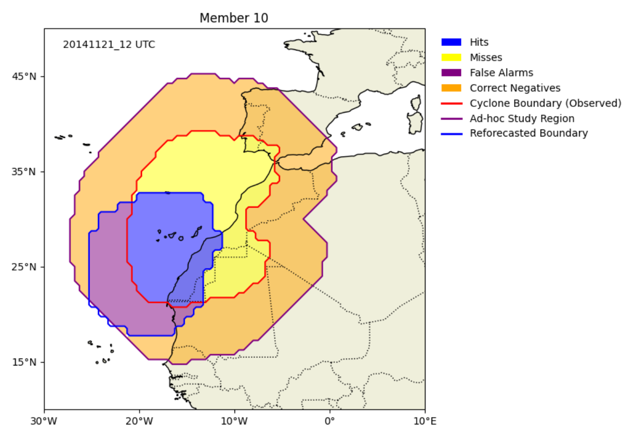

Figure 2. An example of the area-based, four-category verification method (Sect. 2.2.2). The red line denotes the border of the observed cyclone in Fig. A1. The purple line delimits the ad-hoc study region corresponding to this cyclone, which is derived by expanding the border of the cyclone by 6 degrees. An example for cyclone prediction, from the reforecast ensemble member 10, with a lead time of 3.5 days is marked with a blue line. The four categories in the contingency table (Table 1), namely hits (in blue), misses (yellow), false alarms (purple), and correct negatives (orange) are shown by the filled areas.

We evaluated the reforecasts for two main variables that are directly relevant to storm impacts, namely cyclone mask and MSLP, which measure areal storm coverage (spatial frequency) and intensity, respectively.

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For the area-based verification, we calculated the following skill scores using the contingency table: hit rate (or probability of detection; POD), false alarm ratio (FAR), Gilbert skill score (GSS), and Hanssen-Kuipers discriminant (HK). The GSS incorporates information from both the POD and FAR, providing a more comprehensive measure of forecast performance. However, because the GSS is sensitive to the base rate of events (Hogan et al., 2010), we also used the HK, which is less affected by the base rate variations (Candogan Yossef et al., 2012). The scores are defined as follows (Roebber, 2009; Hogan et al., 2010):

$$\mathrm{POD} = \frac{hits}{hits + misses} \tag{1}$$

$$\mathrm{FAR} = \frac{false\ alarms}{hits + false\ alarms} \tag{2}$$

$$\mathrm{GSS} = \frac{hits - hits_{\mathrm{random}}}{hits + misses + false\ alarms - hits_{\mathrm{random}}}, \tag{3}$$

where

$$hits_{\mathrm{random}} = \frac{(hits + misses)(hits + false\ alarms)}{total}.$$

$$\mathrm{HK} = \frac{hits}{hits + misses} - \frac{false\ alarms}{false\ alarms + correct\ negatives} \tag{4}$$

To evaluate the performance of the model in forecasting HPE-associated cyclones for different seasons, a season-based analysis for all HPE-associated cyclones was performed. For this purpose, we calculated the average values of POD and FAR as well as their ensemble spread for reforecasts with lead times from 0.5 days to 15.5 days. For each cyclone, the POD and FAR are calculated by averaging the values from the 10 ensemble reforecast members at the corresponding lead time. The number of cyclones with available reforecasts is recorded for each lead time. For verification with respect to a base state, GSS and HK values are computed for each region of the Sahara and each season for two lead times (3.5 and 10.5 days). We defined *hit members* as reforecast members where the skill (GSS or HK) exceeds an arbitrary threshold of 30% for certain lead times and *hit counts* as the number of hit members for each case.

We also calculated the MSLP root mean square error (RMSE) for reforecasts with lead times ranging from 0.5 to 15.5 days relative to their corresponding ad-hoc study regions. For each forecast lead time, the MSLP RMSE values for the ad-hoc study region were averaged across the 10 members to obtain the representative RMSE for the verification case. Then, we averaged the MSLP RMSE across all events with the same lead times for each season.

2.2.3 Saharan cyclone classification according to skill

To evaluate model performance and relate forecast skill variations to large-scale atmospheric conditions, we classified events according to their reforecast GSS values. The upper 40% and lower 40% of these events were classified as high- and low-skill

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cases, respectively. To analyze their associated large-scale environments, we constructed composites of anomaly fields for three key variables (MSLP, GH500, and T850) averaged separately over the high- and low-skill groups. These anomalies were calculated by subtracting the corresponding monthly climatological mean from the large-scale fields corresponding to 12 UTC on the dates of the events. Monthly climatologies were derived from ERA5 reanalysis data by averaging absolute fields at 12 UTC for all dates in each month from December 2000 to November 2020. Statistical significance of the GH500 anomaly fields was evaluated using a Student's t-test at the 0.05 significance level ($\alpha = 0.05$).

3 Results

3.1 Temporal and spatial variability of forecast skill

To evaluate the predictability of HPE-associated cyclones in the reforecasts, we compute their forecast skill metrics: POD and FAR based on the overlapping areas of observed and forecast cyclones (see Sect. 2.2.2 for their respective definitions). Generally, the forecast skill of HPE-associated cyclones gradually decreases with lead time (purple curves, Fig. 3). However, the temporal variation in forecast skill varies seasonally. Specifically, on the short-range forecast timescale (up to 3.5 days), the forecast skill for winter (Fig. 3d) is higher than in summer, with a lower FAR (Fig. 3b). Moreover, according to the distribution of forecast skill at these lead times, the spread of POD values is much smaller in winter than in summer (purple boxplots, Fig. 3b,d). In contrast, on the medium-range (4 to 10 days) and extended-range timescales (11 to 15 days), the forecast skill for summer is higher than in winter; however, winter POD spread is still smaller (Fig. 3b,d), at all lead times.

Next, we evaluate the forecast skill against the climatological cyclone frequency over the Sahara (solid black line). The average POD in summer is higher than the climatological cyclone frequency (plus one standard deviation), even at lead times longer than 10 days (Fig. 3b). However, at the same time, the average FAR increases to around 60%, indicating a relatively large number of false alarms. Thus, while the median and average POD values in winter decrease rapidly with lead time, the decrease rate in summer is slower, resulting in a higher skill at longer lead times (Fig. 3b,d).

During spring and fall, the temporal variation of skill is similar to winter, with relatively rapid decreases with lead time at short lead times, yet the POD and FAR values remain closer to those of summer for medium- and extended-ranges (Fig. 3a,c). Thus, the forecast skill is close to that of a climatological forecast in spring and winter, and higher than the skill of a climatological forecast in fall, as well as in summer.

To further examine changes in the prediction skill of HPE-associated cyclones beyond the area-based skill metrics, we examine seasonal variations in the RMSE of MSLP in the reforecasts. RMSE is commonly used to show forecast bias. The magnitude of RMSE is strongly season-dependent, with the largest errors in winter, smaller errors in spring and fall, and smallest errors in summer (Fig. 4). Despite this seasonal dependency, the temporal variation of RMSE still shares some common features between the seasons. The average RMSE for all seasons except summer exceeds their corresponding average MSLP standard deviations beyond a lead time of 5.5 days (Fig. 4). In summer, the average RMSE generally remains below the average MSLP standard deviation, even at a lead time of 8.5 days, providing further evidence that the predictability for summer extends

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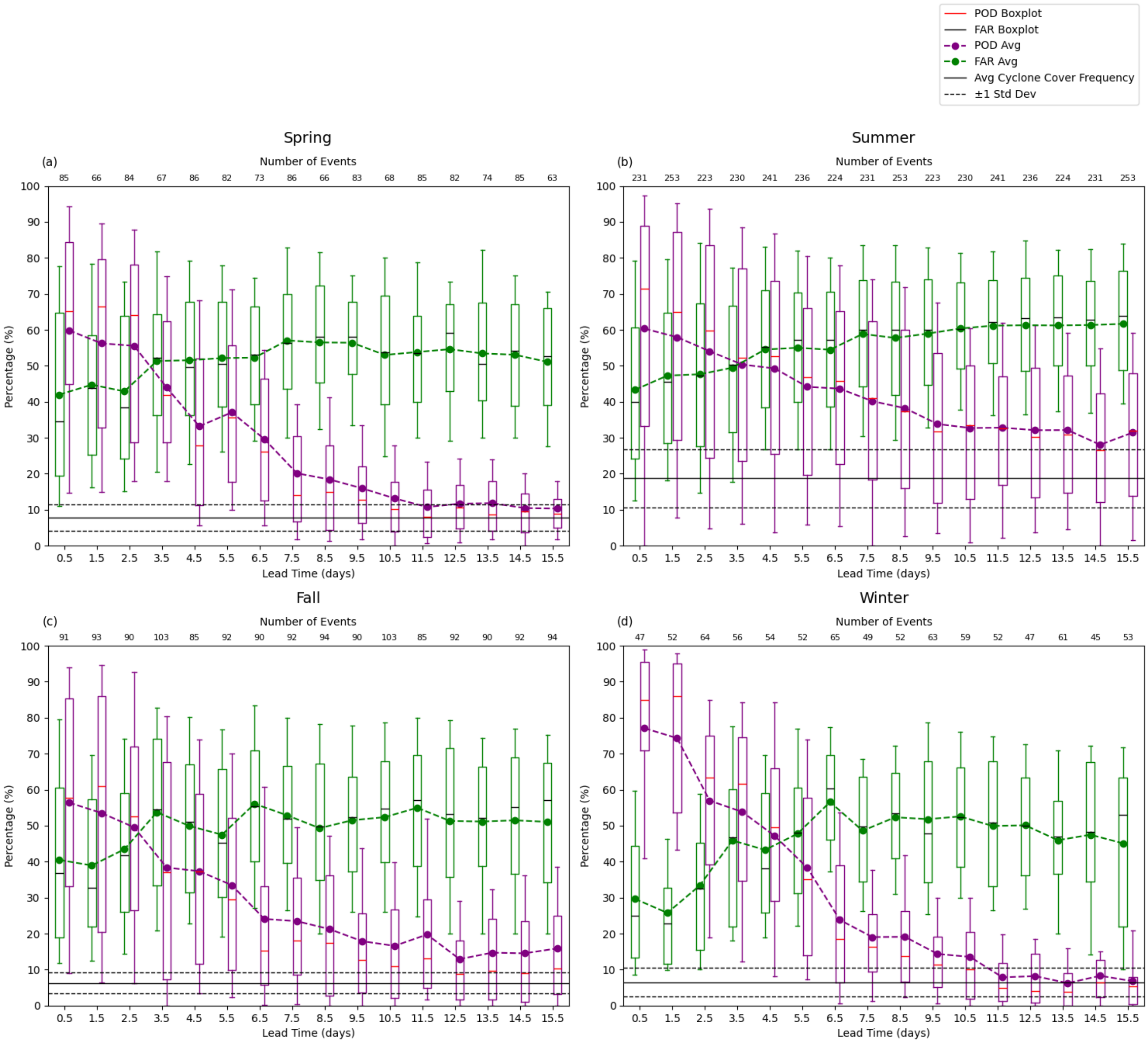

Figure 3. Probability of detection (POD) and false alarm ratio (FAR) of HPE-associated cyclones by lead time and season. Average POD (purple) and FAR (green) and their distribution in ECMWF reforecasts with lead times from 0.5 days to 15.5 days, separated for 4 seasons (a–d) for all HPE-associated cyclones in the study region. The numbers above each box plot correspond to the number of events that have available forecasts at this lead time. The black solid line shows the average climatological frequency of cyclone coverage, computed as the weighted cyclone frequency at each grid point of each cyclone area. The black dashed lines mark one standard deviation of the climatological frequency.

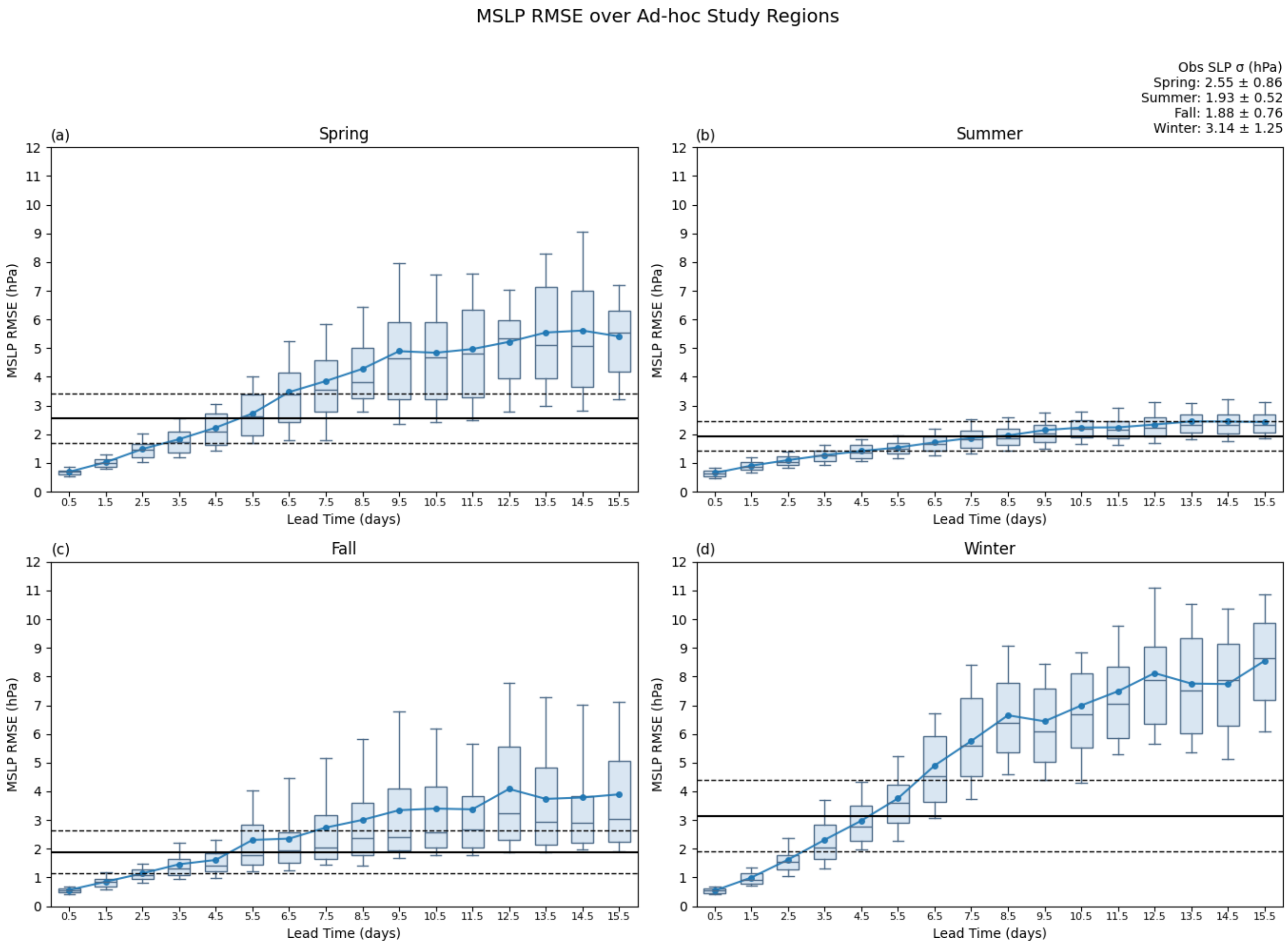

Figure 4. Root mean square error (RMSE) of HPE-associated cyclones by lead time and season. Similar to Fig. 3 but for RMSE. The seasonal mean standard deviation values and their standard deviations are summarized in the upper-right corner.

longer than the other seasons. It is noteworthy that the average RMSE begins to stabilize after the lead time increases to ∼13.5 days (Fig. 4), which is longer than the lead times after which the average POD and the average FAR remain stable (Fig. 3).

The variation in forecast skill exhibits strong regional dependency across the Sahara. Here, we further analyze the regional variation in the forecast skill at lead times of 3.5 and 10.5 days (Fig. 5 and Fig. 6, respectively). The choice of a short-range lead time of 3.5 days corresponds to the lead time at which the POD and FAR are close to each other, while the choice of 10.5 days corresponds to the extended-range forecast lead time at which the POD values are close to their minimum (Fig. 3).

At the lead time of 3.5 days, the forecast skill (measured by the number of members surpassing a GSS threshold; Sect. 2.2.2) exhibits mixed results across the study region, with some distinct spatial patterns (Fig. 5). In summer, high-skill cyclones (defined here as cyclones with hit counts greater than 5 members) are concentrated in the southwestern part of the Sahara,

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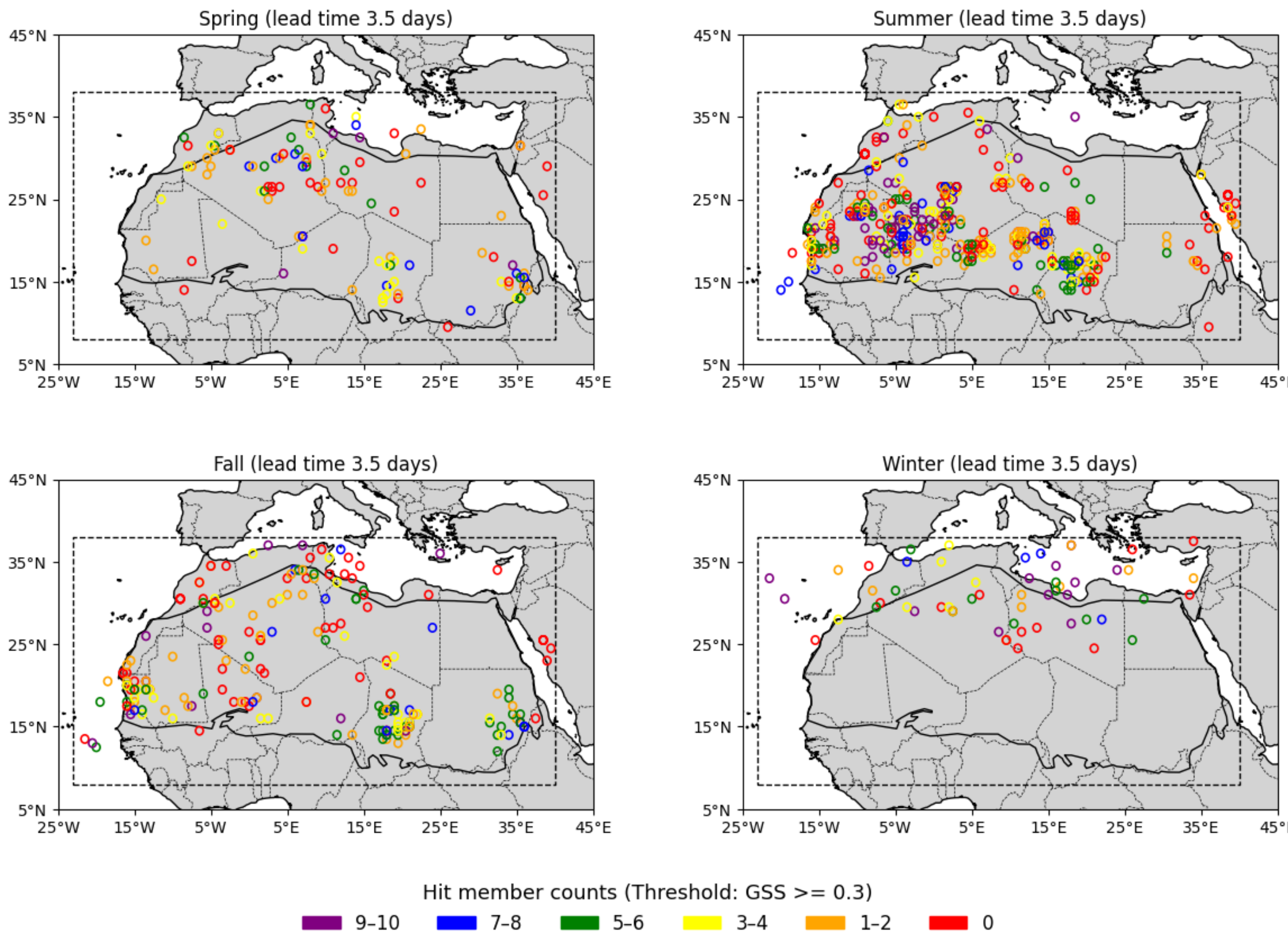

Figure 5. The distribution of hit counts (according to the number of forecast ensemble members) of all cyclones located within the study region for four seasons at a lead time 3.5 days. Circles show the locations of cyclone centers. Colors refer to the groups where the number of hit members are located.

where HPE-associated cyclones are also more frequent. In winter, the number of high-skill cyclone forecasts is lower in the central part of the Sahara and mostly higher over the central Mediterranean. In fall and spring, high-skill cyclone forecasts tend to be located in the southeastern Sahara, with mixed hit count values over the rest of the domain.

As the lead time increases to 10.5 days, the number of high-skill cyclones decreases dramatically throughout the domain (Fig. 6). A higher concentration of high skill forecasts is observed over the southeastern Sahara during spring and fall, and over the southwestern Sahara during summer. In winter, almost all cyclones exhibit near-zero forecast skill at these lead times. The high number of ensemble members with high skill at the lead time of 10.5 days for summer, compared to other seasons, can be attributed to the higher climatological frequency of cyclones in the western part of the study region (Stephenson et al.,

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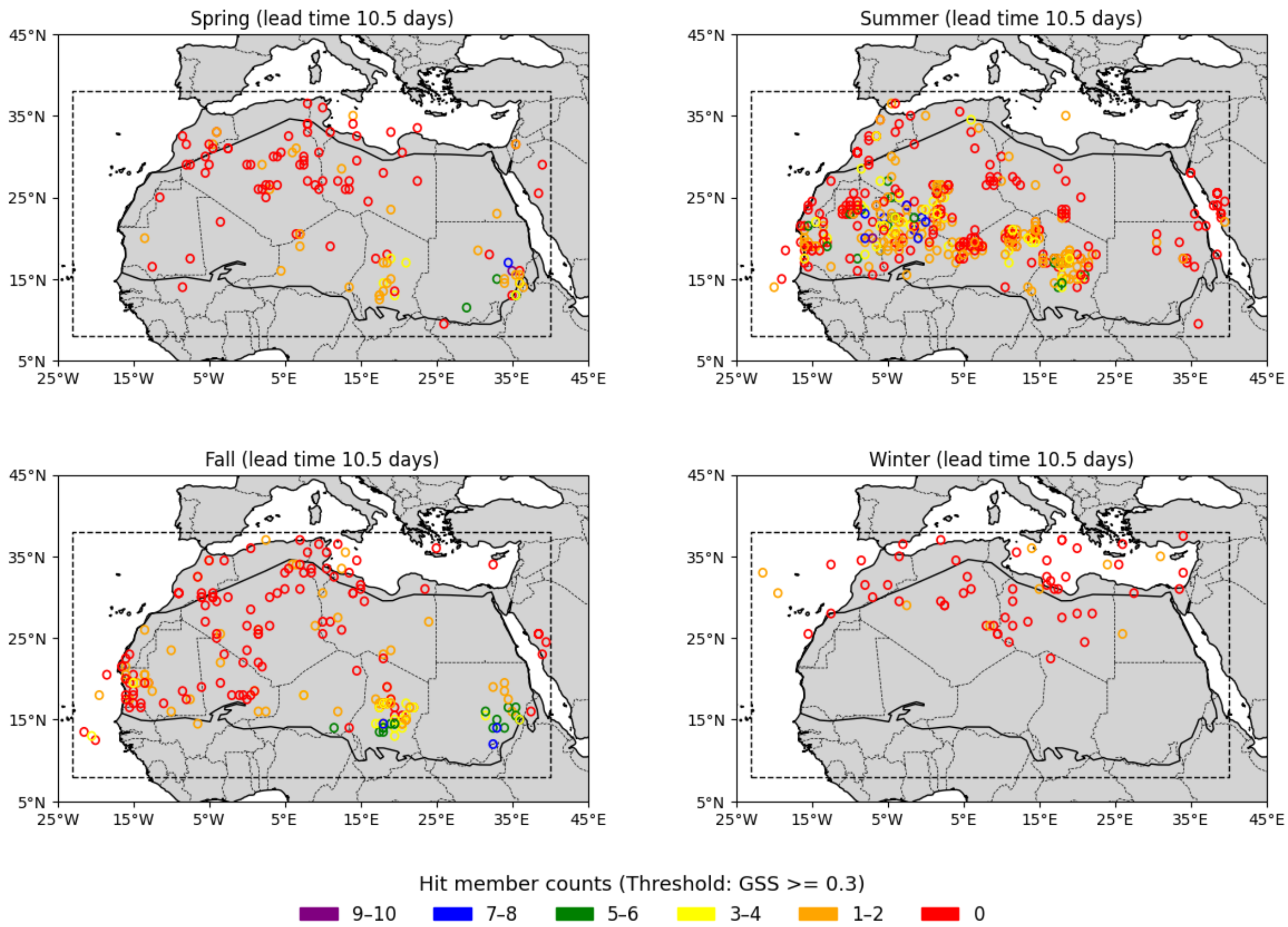

Figure 6. Similar to Fig. 5, but for forecast lead time of 10.5 days.

2008), as well as to their persistence. Therefore, to verify the robustness of these results, we also compute the skill based on the HK metric (Sect. 2.2.2). Although the HK-based skill is generally higher than the GSS-based skill, the HK-based skill shows similar spatial patterns to those shown with GSS (Fig. A2 and Fig. A3), further indicating that the forecast skill in summer is higher than a random forecast on the medium-range or extended-range forecast timescales.

3.2 Association of large-scale circulation patterns with predictability of northern Sahara cyclones

In this section, we focus on the cold-season northern Sahara, since most HPEs there are associated with surface cyclones (Sect. 1 and Fig. 1). These cyclones are deeper compared to southern Sahara cyclones, and tend to originate from the North Atlantic storm track. To identify sources of forecast bias in these cyclones, we explore the large-scale factors that lead to enhanced or reduced storm predictability. Specifically, we analyze large-scale circulation patterns associated with the high- and low-skill

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cases with respect to their GSS scores during the extended-winter season (between October and April) in three subregions of the northern Sahara (Region I–III in Fig. 1) . This analysis is performed using forecasts with lead times of 5.5 and 10.5 days (Fig. 7 and Fig. 8, respectively). Performing the analysis over both short–medium- and medium–extended-range forecasts helps distinguish what dominant large-scale circulation patterns are identified on different forecast ranges. For each composite, anomaly fields averaged over the high-skill and low-skill reforecasts for GH500 (color shading), MSLP (black contours), and T850 (blue contours) are shown (Fig. 7 and Fig. 8). Similar analysis for the meteorological winter season (December to February) was performed (not shown), exhibiting similar results, yet with a smaller sample size.

At forecast lead time of 5.5 days, high-skill cases in the northwestern Sahara (Region I) are generally associated with deeper cyclones (measured by MSLP anomalies) over the western side of the region and a cold anomaly to the southwest of the MSLP anomaly, while low skill is exhibited for shallow and more easterly located cyclones (Fig. 7a,b). The high-skill cases are also associated with a north–south MSLP dipole pattern over the eastern North-Atlantic (as in Rex-type blocking; Rex, 1950), with the positive geopotential height anomaly located south of Iceland and west of Ireland. This high pressure system is a part of a zonally extended high anomaly in the high-skill cases, while in the low-skill cases, the high is located more to the northwest, over Iceland, and is not extended further to the east. In the other two northern subregions, deeper cyclones also generally correspond to the high-skill cases (Fig. 7c–f), especially in the northeastern Sahara (Region III). Apart from the intensity of the cyclones, the forecast skill for the northern Sahara (Region II) is relatively low when both the Icelandic low and the Azores high are stronger than climatology (Fig. 7d). In the northeastern Sahara (Region III), the difference between the high- and low-skill cases is accentuated – forecasts with high skill are associated on average with deeper surface cyclones, with a clear thermal structure (cold anomaly to the southwest of the cyclone and a shallower warm anomaly to the east), and are accompanied by an upper-level negative anomaly resembling a cutoff low, with a series of highs surrounding this low (Fig. 7e). In contrast, low-skill forecasts are associated with shallower surface cyclones, on average, and a series of high pressure anomalies extending at around latitude 60°N, peaking near Iceland (Fig. 7f).

Compared with the 5.5-day lead time, the patterns in the high- and low-skill cases for the northwestern Sahara (Region I) at a 10.5-day lead time are generally similar, with a few exceptions: (a) the positive MSLP anomaly in the high-skill cases is weaker and does not extent eastwards, (b) a warm anomaly and a more prominent upper-level high pressure anomaly appear to the east of the region in the low-skill cases, and (c) the high over Iceland in the low-skill cases is less prominent (Fig. 8a,b). For the same lead time, the patterns in the central northern Sahara (Region II) are quite similar to the ones for the 5.5-day lead time, although the prominent high over Europe disappears in the high-skill cases (Fig. 8c,d). Interestingly, while the wave pattern exists in the high-skill cases for the northeastern Sahara (Region III), albeit with a lower magnitude, for the 10.5-day lead time, the low-skill cases are associated with an eastward shift in the position of the ridge from the North Atlantic towards the UK and Scandinavia (Fig. 8e,f).

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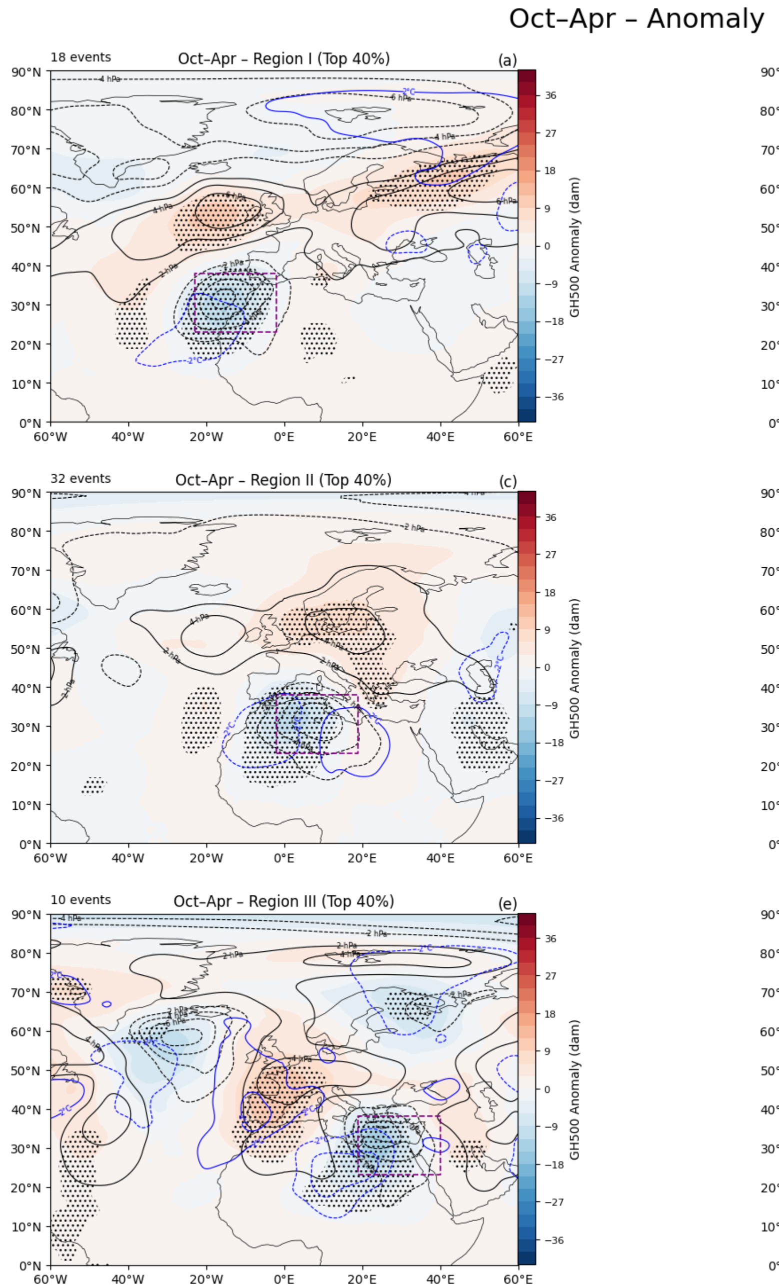

Figure 7. Average GH500 (shadings), MSLP (black contours), and T850 (blue contours) anomaly fields for the high- (a,c,e) and low-skill cases (b,d,f) defined according to their corresponding GSS values for reforecasts with a 5.5-day lead time. Each row represents a different region in the northern Sahara, between October and April. The number of cyclones in each group is annotated on the top left of each subplot. Hatching represents GH500 anomalies that are significant at α=0.05.

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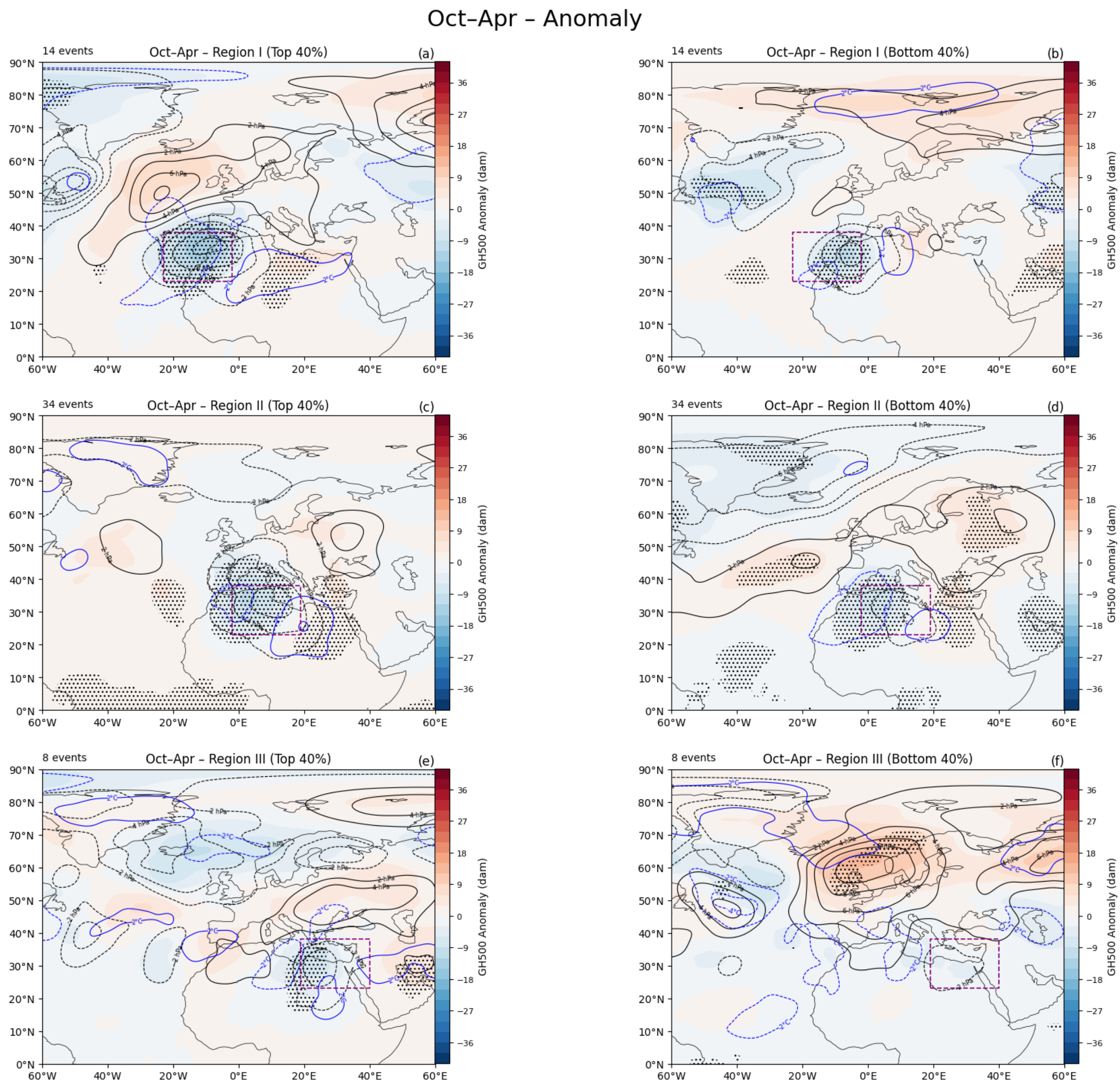

Figure 8. Similar to Fig. 7, but for reforecast lead time of 10.5 days.

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4 Discussion and Conclusions

In this study, we investigate the predictability of cyclones associated with the occurrence of heavy precipitation in the Sahara, focusing on their temporal, regional, and seasonal variability. While precipitation forecasts in arid regions often show limited skill, making it difficult to anticipate both flood hazards and opportunities for water-resource replenishment, increased cyclone predictability offers a pathway to extend the effective lead time for such high-impact events. For this purpose, we use a catalog of HPE-associated surface cyclones, independently identified from satellite observations. The predictability of these cyclones is then evaluated using 10 ensemble member ECMWF reforecasts, with each member verified against ERA5 reanalysis. Verification of cyclone predictions requires an integrated perspective that accounts for the intensity, structure, and location of the cyclone at each lead time. Therefore, we applied an area-based ('feature-oriented') framework for evaluating the forecast skill at lead times ranging from 0.5 to 15.5 days.

The geographic location and season impact cyclone predictability across the Sahara. Generally, the highest short-range skill of HPE-associated cyclones is in winter (Fig. 3), when HPE-associated cyclones are found mainly in the northern part of the Sahara. At longer lead times, however, a higher skill is found in summer and fall, and the region of relatively high skill shifts southward (Fig. 6). Interestingly, summer cyclone forecasts remain skillful compared to a random forecast even on the medium- and extended-range timescales, emphasizing the potential for longer predictability of high-impact storms in this season. Across seasons, the average skill for cyclones remains unchanged after a lead time of about 10.5 days, suggesting that the skillful prediction limit for both winter and summer is around this threshold. This predictability limit coincides with that indicated by Zhang et al. (2019), although they obtained this limit for midlatitude weather systems from the perspective of error variance in prediction models with higher resolution.

The sensitivity of cyclone forecast skill to geographic location and season reflects the distinct characteristics of HPE-associated cyclones in the Sahara, notably their interaction with the large-scale flow patterns. Over the northern Sahara, deeper cyclones are better predicted; a promising result given that cyclone depth is commonly associated with stronger dynamical forcing and a higher likelihood of producing high-impact weather. In some cases, these cyclones seem to be associated with a mid-tropospheric Rossby wave pattern, extending either north–south or south–east from the North Atlantic towards the northern Sahara (Fig. 7 and Fig.8). But Rossby waves are known to be associated with either high or low predictability (see also Prestel-Kupferer et al., 2024): Persistent Rossby wave packets are associated with enhanced predictability and the occurrence of extreme weather events (Wirth and Eichhorn, 2014; Grazzini and Vitart, 2015). However, these Rossby wave packets may also act as "predictability barriers" over the North Atlantic, particularly for forecasts initialized before their onset, thus limiting the forecast skill (Sánchez et al., 2020; Prestel-Kupferer et al., 2024). Furthermore, in the downstream region of Rossby waves, the growth of forecast errors and ensemble spread can lead to a decrease in predictability (Baumgart et al., 2018; Rodwell et al., 2018; Zheng et al., 2013). Furthermore, Rossby wave breaking (RWB) is known to be a key driver for precipitation in arid regions, with contributions of up to 90% of daily precipitation extremes in arid regions located equatorward and downstream of the midlatitude storm tracks (De Vries et al., 2024). Over the northern Sahara, the occurrence of HPE-associated cyclones is potentially linked to RWB, coinciding with the findings of Tamarin-Brodsky and Harnik (2024, see their Fig. 4), showing that

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there are more cyclones in the northern Sahara amid anticyclonic RWB events, compared to cyclonic RWB events. Furthermore, this pattern suggests preferred cyclone activity over the northern Sahara for a positive NAO phase (Benedict et al., 2004; Franzke et al., 2004; Messori and Caballero, 2015). Our findings suggest that Rossby waves are associated with both increased and decreased predictability (Fig.7 and Fig.8), implying that improved understanding of Rossby waves and their interaction with cyclones over the Sahara, can help to improve model accuracy in predicting HPE-associated cyclones.

In the southern Sahara, in contrast to the north, the generation of surface cyclones relies on latent heat release during moisture convection processes and sensible heat at the surface (Gaetani et al., 2017; Maranan et al., 2019), rather than baroclinic instability in the midlatitudes (Thorncroft and Flocas, 1997), whose predictability requires methods beyond this research to study. For HPEs not associated with surface cyclones, especially in the extreme arid areas of the northeastern Sahara, other systems, such as tropical plumes (Yokochi et al., 2019), reversed jet axis (Dayan and Abramski, 1983), and mesoscale convective systems (Trzeciak et al., 2017), need further investigation to better understand the predictability of these non-cyclone-associated HPEs.

Traditional cyclone verification methods evaluate cyclone predictability based on tracking of cyclone centers and intensity biases (e.g., Froude et al., 2007; Neu et al., 2013; Rudeva et al., 2014; Korfe and Colle, 2018). However, these methods do not take into account situations in which there is a small spatial or temporal mismatch between the forecasted and observed cyclones (the *double penalty problem*; Gilleland et al. (2009)). To overcome this issue, our study uses an area-based method to assess the forecast skill of cyclones. In this way, we allow for the verification of cyclones even in situations in which other methods would have underestimated the practical forecast skill. Better assessment of case studies that are forecasted but not observed (i.e., false alarms) and cases that are observed but not forecasted (i.e., misses), can help to identify sources of spatial and temporal forecast errors in the Sahara, as well as in other regions.

Additionally, a larger sample size, for example, obtained by including more hindcasts or ensemble forecasts that include up to 100 ensemble members, can increase the statistical robustness of the analysis. Moreover, since there are more than 12000 cyclone-associated HPEs and more than 3000 HPE-associated cyclones in the whole study region between the years 2000 and 2020, extensive computational resources are required to implement more complicated methods. Here, we provide insights into the broader predictability across the entire Sahara over timescales of days to weeks. Future studies, focusing on specific regions and specific case-studies could shed light on the synoptic-scale processes involved and how predictability of cyclones is modulated throughout their lifecycle. Future studies using more sophisticated methods, such as multiple linear regression and generalized additive models, can further identify and isolate factors that may act as cyclone predictors over arid subtropical regions.

In summary, our analysis suggests that seasonality and dominant circulation patterns exert a strong control on predictability. Further studies of potential relationships between cyclone intensity and large-scale atmospheric circulation patterns are required to determine the relative role of these factors, as well as cyclone characteristics, for predictability. A better understanding of the mechanisms governing cyclone predictability in this region will help provide improved HPE forecasts in arid subtropical flood-prone regions, thus mitigating their devastating impacts.

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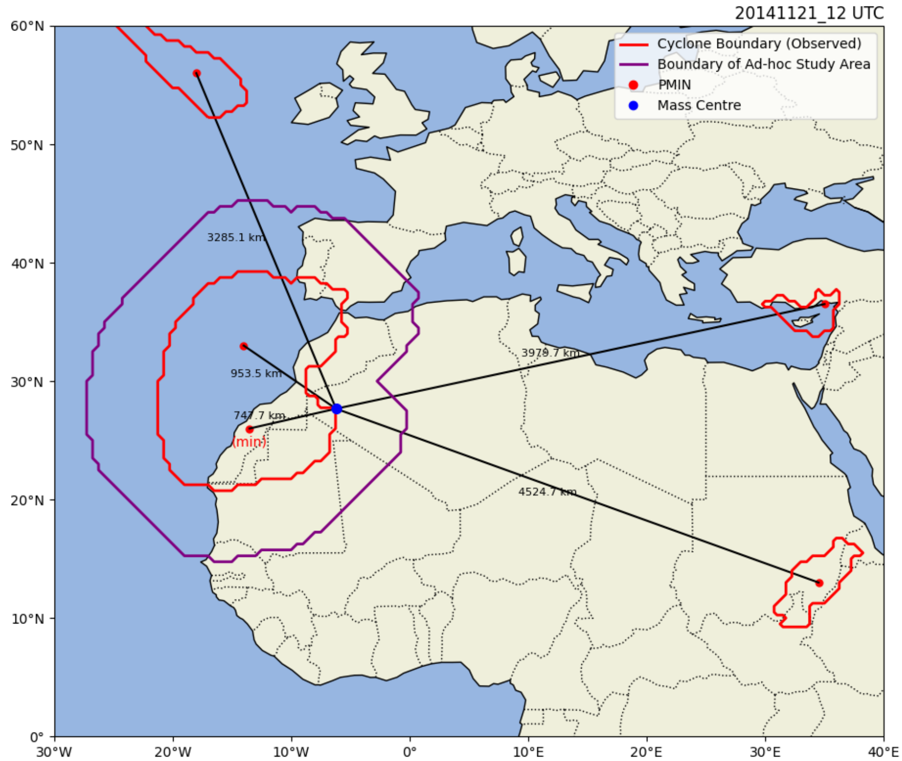

Figure A1. Association of a cyclone with a HPE. The blue dot represents the mass center of an example HPE from 20–24 November 2014. Red dots represent the cyclone centers (minimum pressure), while the red lines denote the borders of cyclones on 21 November 2014 (date of maximum precipitation volume for this HPE). The distances between the mass center and each cyclone center are annotated in the plot. The pressure minimum with the shortest distance to the precipitation mass center is marked with (min) and its corresponding cyclone is the cyclone we have marked as associated with this specific HPE. The border of the associated cyclone is expanded by 6 degrees to obtain an ad-hoc study region (purple line).

Appendix A: Figures

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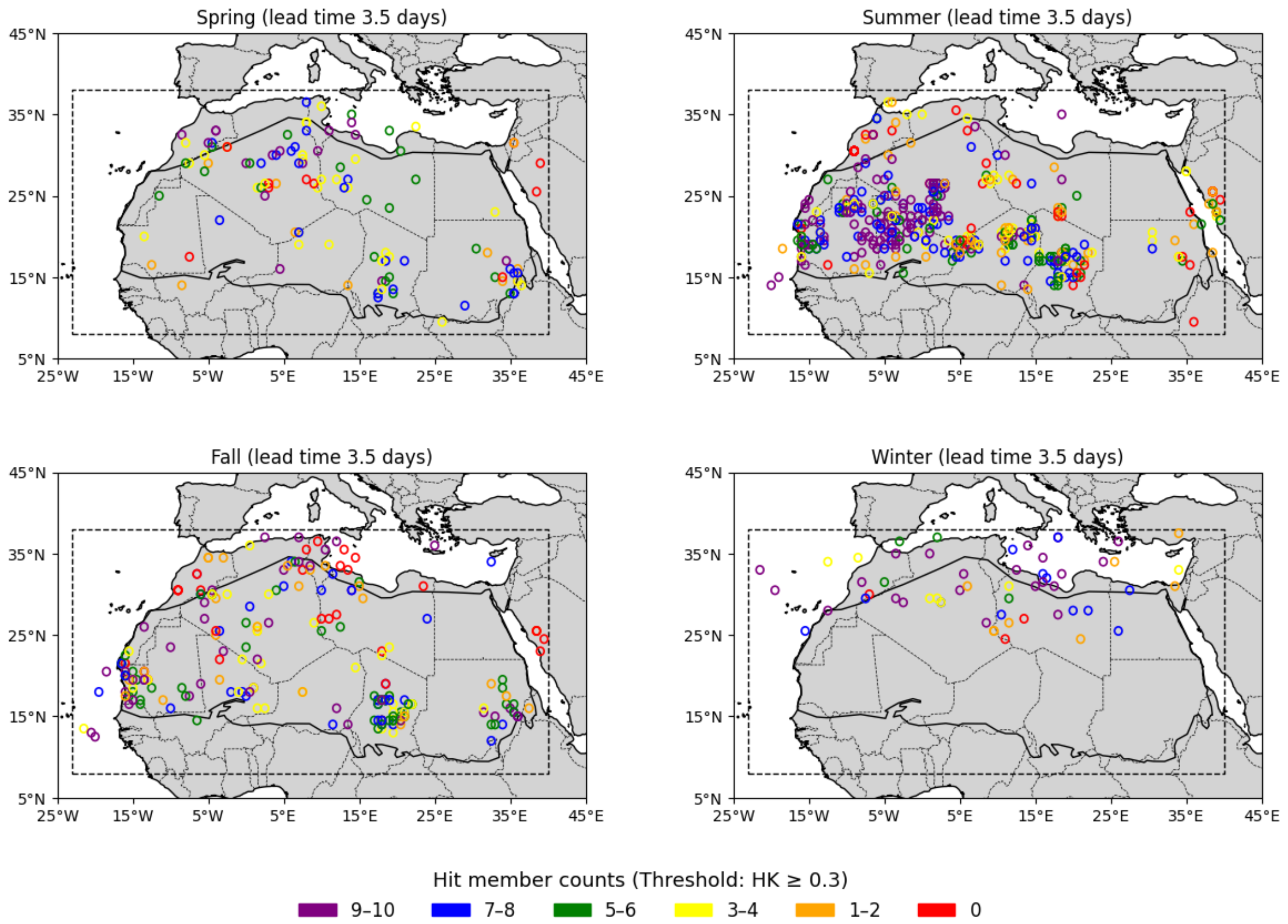

Figure A2. Similar to Fig. 5, but for the forecast skill measured with the HK.

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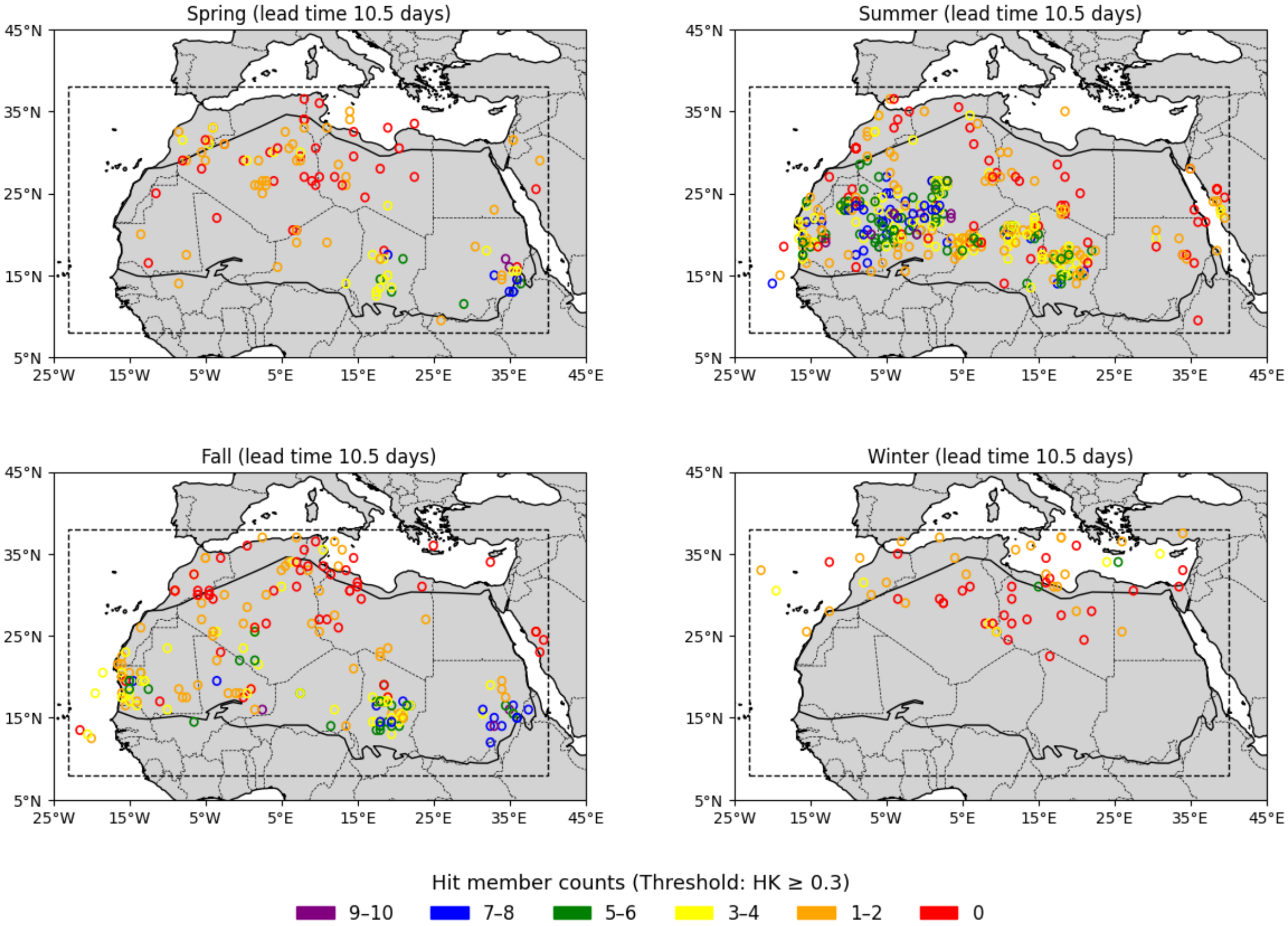

Figure A3. Similar to Fig. 6, but for the forecast skill measured with the HK.

Data availability. ERA5 reanalysis dataset (Hersbach et al., 2020) is freely available through the Copernicus Climate Change Service (Copernicus Climate Change Service (C3S), 2023). The forecasts used in this study are available via the S2S dataset hosted by ECMWF (European Centre for Medium-Range Weather Forecasts, 2015). The Saharan HPE dataset is available through Armon et al. (2024).

315 *Author contributions.* HAG and MA designed the study. GL carried out the analysis and visualizations. All authors contributed to the writing and editing of the manuscript.

Competing interests. The authors declare that no competing interests are present.

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