Extreme precipitation events are becoming less frequent but more intense over Jeddah, Saudi Arabia. Are shifting weather regimes the cause?

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Abstract
This study analyses the connection between extreme rainfall events in Jeddah, Saudi Arabia, and synoptic-scale weather patterns over the Arabian Peninsula. Mean rainfall follows a decreasing trend; however, the number of rainy days has increased. Interestingly, extreme rainfall is becoming less frequent but shows an increased intensity. Here we utilize self-organizing maps (SOMs) to identify the weather patterns of the most intense rainy days and the synoptic systems causing extreme rainfall in the Jeddah region. Three main weather patterns that cause heavy rainfall events over Jeddah during the cooler months (November–April) are identified, all reflect tropical-extratropical interactions. Extreme events in the early period (1979–1998) are characterized by a stronger tropical influence and local precipitation patterns, while a stronger extratropical forcing and higher extreme rainfall amounts are spotted in the late period (1999–2018). Our results suggest that in recent decades, the mechanism causing extreme rainfall over the city of Jeddah has shifted toward a weather regime with stronger extratropical influence.

KEYWORDS
City of Jeddah, extreme precipitation, self-organizing maps

1 INTRODUCTION
Rainfall is sparse and highly variable in intensity over the city of Jeddah, a port city on the Red Sea, and the second-largest city in the Kingdom of Saudi Arabia (KSA). It typically occurs as isolated, episodic convective events during the cooler months, November–April (El Kenawy and McCabe, 2016; Yesubabu et al., 2016; Dasari et al., 2018; de Vries et al., 2018). Extreme rainfall events in the region are generated by mesoscale convective systems (MCSs), which are important weather-related catastrophic hazards (de Vries et al., 2016; Yesubabu et al., 2016; Dasari et al., 2018; Luong et al., 2019). MCSs produce precipitation that covers relatively large areas (100 km or more in extent), with intense rainfall and strong winds (~30 minutes), followed by a longer period of steadier and lighter rainfall (Houze, 1993). MCSs mainly occur in this region during the cooler months, typically in conjunction with more intense extratropical systems. Very heavy rainfall over short periods of time may result in fast-flowing surface runoff, which can quickly turn into raging rivers and causes flash floods due to the limited infiltration capacity of dry soils (Deng et al., 2015; de Vries et al., 2016). In recent years, MCSs in the region have been reported to cause hundreds of deaths and estimated damage of more than US$ 1 billion (ALKhalaf and Abdel Basset, 2013; Haggag and El-Badry, 2013; de Vries...
et al., 2016; Yesubabu et al., 2016). One of the most damaging events is a flooding of Jeddah on November 25–26, 2009. MCS-driven rainfall extremes in the region are projected to intensify under current climate projection scenarios (Tabari and Willems, 2018) due to an exponential increase in the capacity of a warmer atmosphere to hold more water vapor (Meeth et al., 2000), in line with the “fewer but more extreme weather events” paradigm (Luong et al., 2017). Understanding the dynamics of the large-scale circulation patterns in which the MCSs develop in the region is, therefore, of critical importance.

Up to date, precipitation climatology analyses in the region are still scarce, partly due to the large study region and limited data. Previous studies such as those of Almazroui et al. (2012), El Kenawy and McCabe (2016) only investigated observed mean rainfall trends, but studies of extreme precipitation events have only garnered attention recently. Case studies of well-known events have been conducted using both global reanalysis (de Vries et al., 2013; de Vries et al., 2016) and regional models (Hagag and El-Badry, 2013; Deng et al., 2015; Yesubabu et al., 2016). Analyzing the regional extreme precipitation characteristics over long timescales, in the order of decades, is particularly important to understand their trends and potential changes of the associated weather patterns. This could also be very useful for other related fields, such as climate modeling.

In this study, we apply the self-organizing maps (SOMs) technique (Kohonen, 1995; Hewitson and Crane, 2002) on atmospheric variables to classify the large-scale circulation patterns of extreme precipitation events over Jeddah. SOM is one of several techniques used to classify large volumes of similar data into different clusters with distinct patterns. It is based on an unsupervised and objective classification procedure that groups events with common or similar patterns that can be displayed as a two-dimensional array. SOM has two main advantages over other cluster analysis techniques: (a) it places similar patterns closer to each other following a smooth transition from one node to another and (b) it prevents the dominant patterns from overshadowing the others (Hewitson and Crane, 2002). SOM is capable of capturing even less pronounced teleconnection patterns, as has been demonstrated for the North Sea-Caspian Pattern by, for example Rousi et al. (2015). This method further preserves nonlinear relationships and directly interprets physical spatial patterns (Murtagh and Hernández-Pájares, 1995; Reusch et al., 2005), which is an important advantage compared to the traditional method of principal component analysis (PCA; or empirical orthogonal function—EOF; Reusch et al., 2005). To investigate changes in weather patterns associated with extreme precipitation over Jeddah, we further explore the changes of identified SOM patterns between two 20-year periods, as in Hewitson and Crane (2002), Lee et al. (2017), who established the connections between the hemispheric teleconnection and temperature extremes over the Northern Hemisphere.

2 | DATASETS AND METHODS

2.1 | Precipitation and reanalysis data

Daily total rainfall (mm) data over KSA are available from a network of meteorological stations maintained by the Saudi Ministry of Water and Electricity (MOE) and The Presidency of Meteorology and Environment (PME). 53 MOE and 78 PME stations have rainfall data with complete records (stations with less than 5% missing values) over the 40-year satellite-era period 1979–2018.

These stations are spatially distributed throughout KSA (Almazroui, 2011; El Kenawy and McCabe, 2016). The stations’ data are used in conjunction with reanalysis data to identify extreme precipitation climatological patterns. We utilize the European Centre for Medium-Range Weather Forecasts ERA-Interim reanalysis (Dee et al., 2011), available on a 0.75° grid for the cooler months (November–April) from 1979 to 2018, for large-scale circulation classification.

2.2 | Self-organizing map (SOM) analysis

We applied SOM analysis to 18 daily-averaged atmospheric variables extracted from ERA-Interim reanalysis: zonal wind, meridional wind, and geopotential height at 850-, 700-, 500-, and 200-hPa pressure levels, potential vorticity at the 330 K potential temperature level, vertically integrated eastward and northward water vapor fluxes, zonal and meridional wind at 10 m, and mean sea-level pressure. These variables have been used extensively in the region to characterize the dynamics behind extreme events (de Vries et al., 2013; de Vries et al., 2016).

We obtained the atmospheric datasets for the whole Arabian Peninsula (AP) (10°–50°N, 0–70°E; Figure 1) during November–April 1979–2018. We then selected 73 of the most extreme events that occurred in Jeddah to analyze the climatology of extremes. The selected number of extreme events was above the 99.5th percentile (daily rainfall above 7 mm day⁻¹). This number is equivalent to a frequency of about two extreme events per year during the 40-year study period (Figures S1 and S2). This threshold provides a reasonable balance between the intensity characterizing extreme events and the resulting number of selected events, enough for statistical
To limit the SOM sensitivity due to the different scales of variables, we normalized each variable prior to training. We describe the dynamics and thermodynamics of the atmosphere (up to the tropopause) by simultaneously analyzing these aforementioned 18 variables. We also train SOM nodes twice to minimize errors: in the first stage, we kept the learning rate constant, and in the second step, we updated the learning rate and neighborhood radius with reduced influence (Kohonen, 1995).

3 | RESULTS AND DISCUSSION

3.1 | Extremes climatology

We aim to relate the observed extreme rainfall days recorded over Jeddah in the past 40 years to large-scale atmospheric circulations patterns in the ERA-Interim atmospheric reanalysis. We first selected a suitable number of clusters by trial and error. We assessed the reliability of SOM clusters using a bootstrapping technique by empirically estimating the distribution of 1,000 SOM errors. We use the 95% confidence interval to test the null hypothesis that the SOM error is not significantly different from the mean. The test suggests that the null hypothesis is rejected at alpha .05, and the SOM maps of the 73 extreme events are statistically significant at the .05 level. Our clustering results suggest three main different weather patterns that cause heavy rainfall events over Jeddah during the cooler months (November–April). Cluster 1 is the most prevalent, with 27 days (36%) mapped. Cluster 2 gathered the lowest number of days (21 days or 28%). Cluster 3 grouped about a third of the days with extreme events (25 days or 34%). Extreme precipitation patterns around the Jeddah area are displayed.
in Figure 1 using both the stations' data and ERA-Interim Reanalysis. Figure 1a–c shows the station record composite mean of precipitation from the days mapped to each cluster. Most stations with the heaviest rainfall are located to the north of Jeddah in Cluster 1, while those corresponding to Cluster 3 are located to the southeast of Jeddah. Cluster 2, meanwhile, shows peaks distributed all around the greater Jeddah region. The ERA-Interim daily rainfall data is in good agreement with observations. Figure 1d–f shows three distinguishable rainfall patterns: very widespread rainfall in the northern AP over Ha’il, Al Quasim, Tabuk, Al Madinah and Makkah provinces with a peak to the northwest of Makkah (C1); a smaller and more compact area of rainfall just north of Jeddah (C2); and an area of peak rainfall over the Red Sea just west of Jeddah (C3), which is not properly captured by ERA-Interim in terms of intensity. Rainfall measurements from the Jeddah station suggest that Cluster 1 has the highest daily rainfall mean (28.6 mm day$^{-1}$) compared to Clusters 2 and 3 (20.6 and 19.4 mm day$^{-1}$, respectively). To put this into perspective, C1 produces, on average, 43% more rainfall than C2 and C3 on the most extreme days. This rainfall analysis further suggests that C1 consists of more intense and organized rainfall patterns, whereas C3 is less intense and less organized. We interpret C2 as being a transition state between C1 and C3.

Next, we investigate the weather patterns of the SOM categories. Figure 2a–c shows the low-level circulation at 850 hPa, and (d–f) the moisture flux of the whole atmospheric column. The 850 hPa circulation, as one component of the SOM analysis, represents the lower 2–3 km boundary layer atmosphere that is important for convective developments in the region. The Northeastern African Anticyclone (NAA) is weakened while the Arabian Anticyclone (AA) is located further away, near the eastern tip of the AP at 850 hPa in C1 (Figure 2a). The weakening of the NAA from low to mid-levels (850–500 hPa) and the retreat of the AA to the southeast pave the way for deep penetration of the extratropical trough into the south of the Red Sea region. The upper-level mid-latitude trough at 500 hPa intrudes deep into the subtropics with a wave intensification pattern (Figure S3a). Southwesterly winds are dominant and intensify over Jeddah. The
mean circulation of Cluster 1, therefore, favors clockwise transportation of tropical moisture from the adjacent Arabian Sea and Red Sea deep into the northern AP, as shown in Figure 2d. The moisture flux peaks over an area about 100 km northeast of Jeddah, with a mean daily value of 300 kg m\(^{-1}\) s\(^{-1}\), while the value over Jeddah is about 280 kg m\(^{-1}\) s\(^{-1}\) (Figure 2d). Since both these dynamic and thermodynamic conditions provide the ideal scenario for deep and organized convection, six out of the top 10 most extreme events belong to Cluster 1.

Regarding the second most prevalent cluster, C3, the two semipermanent anticyclones (NAA and AA) are merged in the low-level circulation at 850 hPa (Figure 2c). The NAA is dislocated to the north of its normal position, while the intensification of the AA allows for the southern lower-level trough at 850 hPa to intrude deep into the northern Red Sea. The upper-level trough at 500 hPa located in the northern Red Sea (Figure S3c) is not as pronounced as in C1. The mean flow is, therefore, also from the southwest toward Jeddah. Low to mid-level transport of tropical moisture also follows the 850 hPa circulation, carrying large amounts of water vapor from the adjacent seas, as shown in Figure 2f. The moisture flux intensity of C3, however, is less than that of C1, with peaks around 500 km south of Jeddah in the Red Sea and a mean daily value of 280 kg m\(^{-1}\) s\(^{-1}\), whereas the value over Jeddah is about 200 kg m\(^{-1}\) s\(^{-1}\), about 30% less than in C1 (Figure 2f). In C3, both the dynamic and thermodynamic conditions are less favorable for convection over the Jeddah region compared to C1; nonetheless, more than a third of the most extreme precipitation events belong to this group.

We interpret the final and least prevalent cluster, C2, as a transition regime between C1 and C3. Here, the NAA and AA are at about the same position and strength as normal at 850 hPa. A low-pressure system is, however, located between the two high-pressure systems at 850 hPa (Figure 2b). This enhances convection over the region on top of the Red Sea trough (RST), which is a low-level pressure trough that extends from the Sudan Monsoon Low toward the Eastern Mediterranean (Elfandy, 1948; Awad and Almazroui, 2016; Figure 3b). The upper-level mid-latitude trough at 500 hPa does not intrude into the subtropics as deeply as in C1 (Figure S3b). Tropical moisture from the adjacent seas, driven by the AA and the cyclone, is also carried clockwise into the northern AP, as shown in Figure 2e. The moisture flux peaks over the area, about 400 km to the south of Jeddah, with a mean daily value of 250 kg m\(^{-1}\) s\(^{-1}\), while the value over Jeddah is about 200 kg m\(^{-1}\) s\(^{-1}\) (Figure 2e).

We finally present composites of the tropospheric circulations and moisture transport and discuss the three distinct patterns for the Jeddah region. The composites of the large-scale circulations and thermodynamic conditions over Jeddah from Clusters 1–3 are illustrated in Figure 3. The RST is present in all three patterns over the northern Red Sea (Figure 3); the trough extends farthest north in C1. The dominant wind and moisture flux directions are southwest, with the extratropical trough at 850 hPa reaching Jeddah in C1 (Figure 3a). In C2, Jeddah stays within the southern part of a cutoff low at 850 hPa and experiences southerly winds and south-southwesterly

![FIGURE 3](image-url)

(a) C1: 36%
(b) C2: 28%
(c) C3: 34%

(a–c) Schematic representations of the large-scale circulation for extreme rainfall days over Jeddah from Clusters 1, 2, and 3 (C1–C3), respectively. Black, red, blue, and green contours represent mean sea level pressure, geopotential heights at 850 and 500 hPa, and vertical integral water vapor flux, respectively. The main features that produce extreme events in each cluster are denoted: Red Sea trough (RST), Arabian anticyclone (AA), upper-level trough (ULT), and moisture flux (MF). The city of Jeddah is indicated by the blue dot.
moisture transport (Figure 3b). In C3, circulation at 850 hPa and moisture flux near Jeddah generally follow a south-southeasterly direction, where Jeddah is located on the eastern flank of a southward extending upper-level trough (Figure 3c). The AA is strongest in C3 and retreats mostly to the east in C1. The upper-level trough at 500 hPa is strongest and propagates deepest into the subtropics in C1 (Figure 3a); indeed, the upper-level circulation is remarkably well presented in this synoptic regime. Mid-latitude forcing is apparent in C1 where the dynamical tropopause (represented as 2 potential vorticity unit (PVU) contours in the mean potential vorticity map, 1 PVU = 10^6 m^2 s^{-1} K kg^{-1}) at 330 K intrudes well below 30 N toward the equator (Figure S4d), and a strong west-southwest subtropical jet is located at 200 hPa over the northern AP (Figure S4a). This forcing is not as strong in C2 where stratospheric air merely intrudes southward of 30 N (Figure S4e), and the jet exhibits a weaker mean speed (Figure S4b). The extratropical forcing in C2 appears more in the form of an open upper-level trough with a strong westerly flow at 500 hPa (Figure S3b). These mid-latitude forcing signatures are faded in C3 with less intense upper-level jet and less stratospheric air penetrating into the troposphere compared to C1 (Figure S4c,f), though intrusion of a mid-latitude upper-level trough is noticeable at 500 hPa (Figure S3b). This means that extreme rainfall in this cluster is mostly affected by tropical air and local low-level interactions, hence, the limited spatial extent of rainfall in this cluster toward the northern part of the AP (Figure 1c,f).

### 3.2 Changes in the 40-year extreme record

The longest record of data that is available for the city of Jeddah is 40 years for both reanalysis and observations. We divide the 40-year rainfall record into two 20-year periods, 1979–1998 and 1999–2018, defined as “early” and “late” periods, respectively, to assess potential changes in rainfall patterns. The observed mean rainfall over Jeddah suggests a decreasing trend, from 10.99 (early period) to 8.58 mm (late period), while the number of rainy days increased from 73 (early period) to 137 (late period). Table 1 outlines the frequency of occurrence (in days) of rainfall extremes over the 40-year record, the early period, and the late period (F, FE, and FL, respectively), and the temporal change of frequency (ΔF) for each cluster. We notice a decrease in the frequency of extreme events from the early (47) to the late (26) period. C3 has the largest number of events, with 18 out of the 47 events during the early period. In the late period, however, C1 has the highest number of events, with 10 out of 26. The changes in the frequency of events for C1–C3 are −7, −3, and −11, respectively, which suggest that extreme precipitation events are shifting from C3 to C1.

Table 1 also displays daily mean rainfall (mm) for the whole 40-year record, the early period, and the late period (R, RE, and RL, respectively) and the temporal change (ΔR) for each cluster. Mean extreme events rainfall for the early and late periods are 21.9 and 25.3 mm, respectively. We applied a Student t-test on the differences in the means of each period. The significance test suggested that changes in C1 and C3 are statistically significant at 95% confidence level, while C2 shows no statistically significant changes. Interestingly, the mean precipitation in Jeddah for the early period (RE = 21.6 mm) suggests that the least intense events occurred under the C1 regime, whereas in the late period, the C1 regime produced the heaviest rainfall (RL = 40.4 mm). Thus, we observe an increasing trend in rainfall intensity and a pattern shift toward a weather regime with stronger extratropical-tropical interactions (C1).

In addition, Figure S5 displays the frequency of occurrence (in days) of extreme rainfall events during each month of the cool season over the 40-year period and over the two sub 20-year periods. Most extreme events (70%) from C1 occurred between December and January (Figure S5a), which explains why the extratropical forcing is stronger in this cluster. In contrast, the majority of events (76%) from C3 occurred within a single month (November), supporting the tropical influence from the low-level trough in this cluster (Figure S5a). Extreme events from C2 are more spread over the months between November and February, indicating its transition position between C1 and C3 (Figure S5a).

The distribution of the events in C1 during the early period is similar to the 40-year record (Figure S5b). In the late period, C1 distribution changes to a narrower timing window; events occur only between November and January with a peak in December (Figure S5c). The

**Table 1** Frequency of occurrence (in days) of extreme rainfall events during the 40-year record, the early period and the late period (F, FE, and FL, respectively) and the temporal change of frequency (ΔF)

| Cluster | F | FE | FL | ΔF | R  | RE  | RL  | ΔR |
|---------|---|----|----|-----|----|-----|-----|----|
| C1      | 27 | 17 | 10 | −7  | 28.6| 21.6| 40.4| 18.7|
| C2      | 21 | 12 | 9  | −3  | 20.6| 22.3| 18.3| −4.0|
| C3      | 25 | 18 | 7  | −11 | 19.4| 22.0| 12.9| −9.1|

*Note: Composite daily mean rainfall (mm) for these extreme rainfall events during the 40-year record, the early period, and the late period (R, RE, and RL, respectively) and the temporal change (ΔR) for Clusters 1, 2 and 3.*
heaviest rainfall events also occur during these 3 months, supporting the stronger extratropical-tropical interactions and heavier rainfall from C1. Finally, the most dramatic change in seasonality distribution occurs in C3 (Figure S5b,c). The number of events in the most popular month of C3 (November) reduces from 15 (early period) to 4 (late period). This further indicates a shift in extreme events weather regime from C3 (tropical influence) to C1 (extratropical influence).

4 | CONCLUSIONS

This study presents an analysis of the connections between extreme rainfall events in Jeddah, Saudi Arabia, and synoptic-scale weather patterns over the Arabian Peninsula. We classified different synoptic systems using the self-organizing maps (SOM) technique, which separates weather patterns leading to the most intense rainy days and identifies synoptic systems causing extreme rainfall events. This technique produces physically meaningful clusters, which are particularly useful in terms of identifying patterns in extreme rainfall events from the observational data.

Mean rainfall over Jeddah from observational data follows a decreasing trend, while the number of rainy days increased. Interestingly, extreme rainfall above the 99.5th percentile (the 73 heaviest rain events in 40 years) shows a contrasting picture. The frequency of extreme events decreased from 47 to 26, but the intensity shows a decreasing trend, while the number of rainy days increased. Interestingly, extreme rainfall above the 99.5th percentile (the 73 heaviest rain events in 40 years) shows a contrasting picture. The frequency of extreme events decreased from 47 to 26, but the intensity increased from 21.9 to 25.3 mm. This finding is in line with the “fewer but more extreme weather events” paradigm.

We identified three principal weather patterns that induce heavy rainfall over Jeddah during the cooler months (November–April). The RST is a prevalent feature in all patterns, suggesting the importance of low-level tropical air masses that provide convective energy leading to extreme rainfall events. Each synoptic regime, however, exhibits different upper-level circulations. In Cluster 1, baroclinicity is prevalent, with the intrusion of warm air in the low levels and cold air from the upper levels, favoring the development of MCSs. Extreme rainfall results from deep equatorial penetrations of cold upper-level troughs (Clusters 1 and 2), whereas extreme rainfall events of Cluster 3 are strongly influenced by tropical air. Furthermore, the interaction of the moisture-laden large-scale southerly flow with the mountain ranges along the Red Sea, such as the Hijaz Mountains to the east of Jeddah, may enhance convection resulting in extreme rainfall.

In summary, our analysis suggests that extreme precipitation patterns over Jeddah are shifting from a tropical influenced regime (Cluster 3) toward a weather regime with a stronger extratropical forcing (Cluster 1), resulting in a decreased rainfall frequency but increased extreme intensity. We conducted our analysis based on observational precipitation records and reanalysis data. The changes in extreme rainfall over the city of Jeddah described here can be further investigated using convection-permitting model simulations, which will be the objective of our future work.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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