Seventy-year disruption of seasons characteristics in the Arabian Peninsula

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Abstract
Climate change has significantly influenced the characteristics of seasons and negatively affected ecosystems and socio-economic life. This study presents a new, objective definition for seasons in the Arabian Peninsula. Specifically, the study determines disruptions in the onset, cessation, and duration of winter, spring, summer, and autumn based on mean intra-annual changes of 12 climatological parameters from 1950 to 2019. Data for climatological parameters were obtained from the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis. These data were analysed using two multivariate statistical methods: principal component analysis and cluster analysis. The results show that the characteristics of the four seasons differ from conventionally defined seasons. The differing characteristics of the four seasons are (a) that winter extends for 91 days, between 2 November (the previous year) and 31 January; (b) spring extends for 111 days, until 22 May; (c) summer extends for 106 days, until 5 September and, finally; (d) autumn completes the cycle, extending for 57 days. To investigate the decadal disruption of seasons’ characteristics, the analysis was performed on the data collected during five overlapping 30-year periods: 1950–1979, 1960–1989, 1970–1999, 1980–2009, and 1990–2019. The most remarkable changes were noticed during the last 30 years. Compared to the 70-year analysis, the 1990–2019 analysis showed extra prolongation in the duration of summer and a shortage in winter, which aligns with the recent warming and drying of the Arabian Peninsula. Summer (winter) lasts for 126 (76) days. All analyses propose that all seasons start earlier, compared with the astronomical definition. The findings of this study are key to understanding the consequences of seasons changes in the Arabian Peninsula. These consequences include impacts on agriculture, water deficits, ecosystems, and land cover.

Keywords
Arabian Peninsula, climate change, cluster analysis, principal component analysis, seasons classification
1 | INTRODUCTION

The astronomical definition of seasons in the Northern Hemisphere includes the boreal winter from 22 December to 21 March (vernal equinox); spring, which ends on 22 June (summer solstice); summer, which ends on 23 September (autumnal equinox); and finally, autumn, which ends on 22 December (winter solstice). Meteorological definitions suggest that each season lasts 3 months, with the four seasons being spring (March, April, and May), summer (June, July, and August), autumn (September, October, and November), and winter (December, and January and February of the next year). However, these definitions might be imprecise under warmer climates. In 1983, Trenberth (1983) questioned the definitions of seasons. He used global air temperature data to determine a more accurate climatic definition for seasons in the United States. Trenberth (1983) noticed that surface temperatures laged behind the solar cycle at different lengths of time that aligned with the distances between regions and oceans (seas). This time lag was 27.5 days in the USA and 32.5 (44) days in the mid-latitudes of the Northern (Southern) Hemisphere. Consequently, Trenberth (1983) concluded that, in the United States, winter starts on 3 December and summer on 4 June, which implies a time lag of 17–20 days in the United States's seasons. Similarly, Ovadiah and Goldreich (1997) defined the Eastern Mediterranean seasons as follows: winter from 12 December to 14 March and summer from 13 June to 12 September.

Defining seasons using a unique index like surface temperature may be inaccurate. Temperature varies spatially based on the relief of regions and land use. Temperature is only one of several phenomena that characterize seasons. As such, several studies have proposed using a synoptic weather typing system to categorize weather conditions. The synoptic system is represented using prevailing climatic parameters in the studied region. For example, Sheridan (2002) used air temperature, cloud cover, dew point, and sea-level pressure to examine changes in the four seasons in North America. In the Eastern Mediterranean, Alpert et al. (2004b) used air temperature, geopotential height, and two wind components (zonal and meridional) from the NCEP/NCAR dataset between 1948 and 2000. To study the intra-annual changes in the Indian summer monsoon season, Xavier et al. (2007) proposed an objective definition of the summer monsoon season based on the impact teleconnection patterns have on the troposphere temperature over Eurasia. Allen and Sheridan (2016) assessed the temporal and spatial changes in the United States’s seasons during the 1948–2012 period using apparent temperature thresholds and upper-level circulation patterns. Kotsias et al. (2020) presented an objective classification of seasons in the Mediterranean region using multiple meteorological parameters during 1949–2018. Kotsias et al. (2020) found substantial changes in the seasons’ characteristics compared with the astronomical definition. Another study (Sparks and Menzel, 2002) applied phenology to evaluate seasonal changes in Europe, studying the cyclic natural events of plant, animal, and bird life in relation to climate. These studies all found disruptions in season characteristics.

Little has been done to investigate the evolution of seasons’ characteristics in the Arabian Peninsula. However, the region experiences numerous phenomena relevant to abrupt changes in seasons (e.g., prolongation of the drought period, precipitation and heat extremes, and seasonal changes in temperature and humidity cycles). Several studies (Evans, 2008; Donat et al., 2014) have shown that the Arabian Peninsula drought season has lengthened due to the principal modes of climate variability. A correlation between wet season precipitation and teleconnection patterns has also been found (Kang et al., 2015; Dunning et al., 2016). These correlations indicate changes in season characteristics (Xavier et al., 2007; Kang et al., 2015; Hochman et al., 2018). Additionally, in the last two decades, the Arabian Peninsula has experienced several flash floods that exceeded regional mean annual averages. Up to 111 mm of rain fell in Jeddah, Saudi Arabia, over only 4 hr on 26 January 2011 (Saeed and Almazroui, 2019). Up to 81 mm of rain fell on 25 November 2015 in Qatar and in the central and eastern parts of Saudi Arabia, causing one fatality and several injuries (FloodList, 2015). Some floods have occurred on unexpected dates, significantly affecting human safety and infrastructure and hindering accelerated urban development. More than 150 mm of rain fell in 1 day in March 2016 in the United Arab Emirates (UAE; Ahmed et al., 2019). Heavy rains caused four fatalities in Oman on 18 May 2019 and several injuries in southwest Saudi Arabia on 22 May 2019 (FloodList, 2019). Therefore, proper investigation of the changes in Arabian Peninsula seasons is vital to save lives and assets.

This study presents a new objective definition of seasons in the Arabian Peninsula. More specifically, the study determines the onset, cessation, and duration of each season based on the mean intra-annual changes of 12 climatological parameters over the last 70 (1950–2019) years. The findings of this study are key to understanding the intra-annual changes to climatic variables across the region. The findings will also help us study the consequences that season changes in the Arabian Peninsula have on the area’s agriculture, water deficits, ecosystems, and land cover.
1.1 Study area

The Arabian Peninsula is located between longitudes 35° and 60° east and latitudes 10° and 35° north, as shown in Figure 1. It includes seven countries: Saudi Arabia, Yemen, Oman, UAE, Qatar, Kuwait, and Bahrain. Elevation in these countries varies from zero near the coasts to 3,535 above mean sea level (amsl) in the western and southwestern regions. The Arabian Peninsula is categorized in the hot desert class (BWh) according to the Köppen climate classification (Peel et al., 2007) and is extremely water-stressed region. Except in Oman, annual renewable water resources do not exceed 87 m³ per capita (Odhiambo, 2017). Over the last two decades, the Arabian Peninsula has experienced remarkable population growth. The population reached 85.2 million in 2019, an 82% increase from 2000 (World Bank, 2020).

2 DATA AND METHODS

2.1 Data

This study acquired 12 climatic parameters from the NCEP/NCAR reanalysis (Kalnay et al., 1996). The NCEP/NCAR reanalysis uses observations of systems to produce quality global climatological datasets for climatic and earth science studies (Wang et al., 2006; Fowler et al., 2007; Allen and Sheridan, 2016; Cassou and Cattiaux, 2016; Sousa et al., 2018). The NCEP/NCAR climatic datasets, accessible at the NOAA Physical Sciences Laboratory, are available in both daily and four-times-daily (6-hr) timescales dating back to 1 January 1948 (https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html; last access on 2 November 2020). The 12 climatic parameters were selected so they can represent the Arabian Peninsula climate in an adequate way, and the geopotential heights were included to represent the synoptic conditions prevailing each season (i.e., the circulation) (Donat et al., 2014; Kang et al., 2015; Attada et al., 2019; Saeed and Almazroui, 2019; Almazroui et al., 2020). Table 1 displays the selected parameters and categorizes them into two groups according to their spatial resolutions. The wind has two components: along the local parallel of latitude (zonal) and along the local meridian (meridional). The zonal wind is positive (negative) if it blows from the west (east), and the meridional wind is positive (negative) if it blows from the south (north).

2.2 Methods

To investigate the mean intra-annual changes in the NCEP/NCAR daily climatic parameters, the study implemented two multivariate statistical approaches: principal component analysis (PCA) and cluster analysis (CA). To this end, the 12 daily climatic parameters were prepared as follows: (a) for each parameter, a Python subroutine was developed to compute the daily average at grid points, creating a matrix where rows represent days
and columns represent grid points; (b) the 12 matrices were then unified into one matrix, dimensioned by 365 rows representing the number of days in a year and 1,696 columns representing all the grid points (Table 1); and (c) the mean intra-annual values were replaced by the 5-day moving average to avoid high levels of noise in daily parameters (Alpert et al., 2004a; Kotsias et al., 2020). The steps were done for the chosen 70-year (1950–2019) and five 30-year periods (1950–1979, 1960–1989, 1970–1999, 1980–2009, and 1990–2019). After preparing the climatic data, PCA and CA were performed.

Principal component analysis is a method that analyses multiple input variables by reducing their dimensionality into principal variables with minimal loss of information. This analysis is an effective way to ease the process of large data set analysis for climatic research (Fowler et al., 2007; Cassou and Cattiaux, 2016; Kotsias et al., 2020). In this study, PCA was performed to reduce the 12 climatic parameters into principal components (PCs). To determine the appropriate number of PCs, we used a scree plot. A scree plot is a visual technique where eigenvalues are plotted from the largest to the lowest against component numbers. The appropriate number of principal components is defined at the point where we can neglect the remaining eigenvalues because they are relatively small. For more information about PCA and scree plot, the reader can refer to Rencher (2003) and Jolliffe (2002).

The cluster analysis is a statistical method used to classify dataset variables into smaller groups called clusters. This method is reliable for developing synoptic climatology (Davis and Walker, 1992; Kalkstein et al., 1996; Reiser and Kutiel, 2007; Kotsias et al., 2020). In this study, CA was performed after the PCA to discover potential relationships among the resulting PCs. The rate of similarity was measured using the squared Euclidean distance method, which represents a geometric distance in multidimensional space. Then, the k-means clustering method was used to minimize within-cluster variances (the distance between data and the corresponding cluster centroid). We suggested that dates over the year can be categorized into groups: in this case, 2, 3, ..., 10. Using an elbow plot, we determined the optimal number of clusters (groups) by noting the location of the bend in the plot. Adding another cluster after the bend did not improve the cumulative total within-cluster sum of squares significantly. In all studied periods, the k-means analysis resulted in four clusters with common climatic characteristics in terms of the magnitude and spatial design of climatic variables. These clusters became the objectively defined periods (i.e., seasons). Additional information about the CA was presented in Rencher (2003) and Jolliffe (2002).

### RESULTS

#### 3.1 Changes in seasons characteristics over the last 70 years (1950–2019)

To identify changes in seasons characteristics during the 1950–2019 period, we determined the number of PCs using a scree plot. Figure 2a depicts the eigenvalues of the 12 climatic parameters. The first two components have eigenvalues of 7.68 and 3.41. The percentage of variance for PC1 was 64.01% and for PC2 was 28.39%.

| Group | Climatic parameters | Spatial resolution (lon. × lat.) | Number of grids in the studied domain (10°N–35°N, 35°E–60°E) |
|-------|---------------------|----------------------------------|---------------------------------------------------------------|
| 1     | 2-m air temperature 1.875° × 1.915° | 13 × 14 = 182                  |
|       | Precipitation rate  |                                  |                                                               |
|       | Convective precip. rates |                              |                                                               |
|       | Total cloud cover   |                                  |                                                               |
| 2     | 500 hPa temperature 2.5° × 2.5° | 11 × 11 = 121                 |
|       | 850 hPa temperature |                                  |                                                               |
|       | 850 hPa specific humidity |                                |                                                               |
|       | 2-m zonal wind      |                                  |                                                               |
|       | 2-m meridional wind |                                  |                                                               |
|       | 500 hPa geopotential height |                              |                                                               |
|       | 1,000 hPa geopotential height |                              |                                                               |
|       | Precipitable water content |                               |                                                               |
Together, the two PCs account for a cumulative percentage of variance equalling 92.40%, suggesting that they successfully represent the parameters. Therefore, we proceeded with the analysis using the two PCs. The contributions of climatic parameters to PCs varied with greater influence from the geopotential heights > 2 m air temperature > 500 and 850 hPa temperatures > total cloud cover, zonal wind, and 850 hPa specific humidity. These parameters, therefore, can best represent the Arabian Peninsula climate. Rashid et al. (2020) linked large-scale atmospheric circulation and the Arabian Peninsula extreme temperature in summer. Saeed and Almazroui (2019) used geopotential height and wind components to analyse the impact of mid-latitude circulation on winter precipitation over the Arabian Peninsula during 1948–2012. Kang et al. (2015) also used the geopotential height data to investigate the multidecadal changes in the relationship between the El Niño–Southern Oscillation (ENSO) and the Arabian Peninsula winter precipitation. After determining the PCs, we identified the appropriate number of groups in the PCs dataset using the elbow method, as shown in Figure 2b. The bend corresponds with the number four, implying that four clusters can be used to define groups appropriately.

For each defined season, the central date was defined as the day closest to the corresponding centroid. The durations of seasons were determined through calculation of the total number of dates categorized in corresponding seasons. Results revealed four objectively defined seasons with different characteristics than conventionally defined seasons. Table 2 presents the characteristics (onset, cessation, and duration) of the Arabian Peninsula’s defined seasons during the 1950–2019 period. Throughout the 70-year period, winter lasted for 3 months. It started on 2 November (the previous year) and ended on 31 January. Spring was the longest season; it followed winter and lasted 111 days, between 1 February and 22 May. Next, summer lasted for 106 days, between 23 May and 5 September. Finally, autumn, the shortest season at only 57 days, completed the annual cycle between 6 September and 1 November. This analysis revealed that all the seasons began earlier than the astronomical definition of seasons in the Northern Hemisphere. Spring onset advanced the astronomical calendar by 49 days, while summer and autumn onsets advanced the astronomical calendar by 31 and 18 days, respectively. Autumn cessation (i.e., winter onset) advanced by 49 days.

Figure 3 shows the mean patterns of the 12 climatic parameters on 24 December, the central date of winter, during the 1950–2019 period. The most prominent climatic features were a strong temperature gradient along the Arabian Gulf and considerable precipitation rates (compared to other seasons) over the southern areas of the Arabian Peninsula, particularly Yemen and southwestern Saudi Arabia. Cloudiness ranged from 14 to 42%, with the lowest values in the southern parts of the Arabian Peninsula. The northern (southern) Arabian Peninsula had 500 hPa temperature of −16.7 to −10 (−10 to −5) °C. All regions in the Arabian Peninsula had 850 hPa temperature between 5.8 and 15°C. The 500 hPa
geopotential height map shows a range of 5,800–5,870 (5800–5,700) m in southern (northern) Arabian Peninsula. The 1,000 hPa geopotential height map shows a range between 136 and 178 m, except southwestern parts which had values slightly lower than 136 m. Higher values of precipitable water content (21.7 kg·m$^{-2}$) were found in the western areas in Saudi Arabia, meaning that more water was available for potential precipitation. As shown in Figure 3, the Arabia Peninsula is affected by negative zonal winds (i.e., blow from the east) up to 3.3 m·s$^{-1}$, while meridional winds values varied between −1.7 and 2.5 m·s$^{-1}$.

Figure 4 shows the mean patterns of the 12 climatic parameters on the central date of spring (30 March). Overall, near-surface air temperature ranged between 16.5°C in northern Arabian Peninsula and 26°C in southeastern Arabian Peninsula. Minimal precipitation (<1.3 mm per day) fell across the Arabian Peninsula in the spring. Dominant characteristics of spring are a cloudiness cover up to 42.5% and minimal convective precipitation rate of less than 1.7 mm/day. Like winter, the 500 hPa temperature ranged between −16.7 and −10 (−10 and −5) °C in northern (southern) Arabian Peninsula. The 850 hPa temperature values varied between 11.7 and 17.5°C in northern Arabian Peninsula, whereas southern parts had values between 17.5 and 21°C. The 500 hPa geopotential heights in spring were typical of winter. On the other hand, the 1,000 hPa geopotential
height map showed lower spring values (~95 m) compared to winter (136–178 m). The 2 m zonal winds were negative and varied up to 3.3 m/day, while the 2 m meridional wind ranged between −1.7 and 2.5 m·s⁻¹. The highest values of meridional winds were noticed in Yemen and Oman.

Figure 5 shows the mean patterns of the 12 climatic parameters during the 1950–2019 period on 8 July, the central date of summer. High rates of warming and drying dominate the summer climate in the Arabian Peninsula. The maximum near-surface air temperature reached 37°C in the Arabian Gulf, compared to 23.7°C in the winter and 26°C in the spring. The latter finding agrees with Attada et al. (2018), who found that surface temperature records in summer had exceeded 35°C in eastern Arabian Peninsula during 1901–2010. The lowest surface air temperature was in western Arabian Peninsula, suggesting the orographic and Arabian Sea cold waters effects (Attada et al., 2019). Nearly no rain fell over the Arabian Peninsula regions during the summer (23 May–5 September). Cloudiness peaked at 56% over southwestern parts of the Arabian Peninsula, while it was less than 14% over northern Arabian Peninsula. The 850 hPa temperature values ranged between 32°C in eastern Arabian Peninsula and 23°C in western Arabian Peninsula.

The 500 hPa geopotential height map showed the highest values in summer compared to other seasons.
This implies that the 500 hPa geopotential heights are higher during the monsoon months (JJAS) than the pre-monsoon months (MAM), suggesting a substantial impact of the circulation on the Arabian Peninsula between pre-monsoon to monsoon periods. The latter finding agrees with Attada et al. (2018), who found a correlation between the Indian summer monsoon and the Arabian Peninsula summer temperature during 1901–2010. The 1,000 hPa geopotential heights were ~95 m in most areas.

Surface zonal wind values were between ~3.3 and 3.3 m s⁻¹, whereas the majority of the Arabian Peninsula had surface meridional winds around ~1.7 m s⁻¹.

Figure 6 shows the mean patterns of the 12 climatic parameters during the 1950–2019 period on 3 October, the central date of autumn. The 2 m air temperature ranged between 23.7 and 30.8°C, with high values over the Arabian Gulf. Minimal rain (<1.3 mm per day) fell during autumn over the Arabian Peninsula. Nearly no cloudiness was found in eastern Arabian Peninsula, while southwestern areas had cloudiness percentages up to 42%. The 500 hPa temperature varied between ~10°C in northern areas and ~5°C in southern areas, while 850 hPa temperature values were approximately 23°C in the whole range. The 500 hPa geopotential height map showed high values between 5,850 and 5,890 m. The 1,000 hPa geopotential height values were ~95 m in most areas.
regions. Aside from northern parts, no considerable zonal wind values were noticed at 2 m over the Arabian Peninsula during the last 70 years, whereas meridional wind values at 2 m were around $-1.7 \text{ m/s}$.

### 3.2 Changes in seasons characteristics during the five overlapping 30-year periods

To discuss the temporal changes in the Arabian Peninsula seasons characteristics, we performed a dynamic analysis for five 30-year periods between 1950 and 2019. These periods are 1950–1979, 1960–1989, 1970–1999, 1980–2009, and 1990–2019. All previous steps in the 70-year analysis were repeated. Outcomes showed four clusters (i.e., seasons) with different seasonal characteristics in all periods. Nevertheless, clusters characteristics, especially onset and cessation dates, were not clear in four periods (all except 1990–2019), compared to 1950–2019. On the other hand, the last 30 years (1990–2019) exhibited the most remarkable and apparent changes in seasons characteristics. Table 3 shows the seasons characteristics (onset, cessation, and duration) for the five overlapping periods in addition to the 70-year analysis, while a detailed discussion of seasonal changes over the last 30-year period is presented in the next section.

The characteristics of the objectively defined seasons differ among the five overlapping 30-year periods. During
The characteristics of the defined Arabian Peninsula seasons during the five overlapping periods in addition to the 1950–2019 period

| Season  | Dates                     | 1950–1979 | 1960–1989 | 1970–1999 | 1980–2009 | 1990–2019 | 1950–2019 |
|---------|---------------------------|-----------|-----------|-----------|-----------|-----------|-----------|
| Winter  | Onset                     | 24 October| 4 November| 1 November| 6 November| 11 November| 2 November|
|         | Cessation                 | 4 February| 31 January| 10 February| 2 February| 25 January| 31 January|
|         | Central                   | 26 December| 16 December| 20 December| 2 January| 18 December| 24 December|
|         | Duration                  | 104       | 98        | 102       | 89        | 76        | 91        |
| Spring  | Onset                     | 5 February| 1 February| 11 February| 3 February| 26 January| 1 February|
|         | Cessation                 | 30 May     | 29 May     | 15 May     | 26 May     | 18 April   | 22 May    |
|         | Central                   | 4 April    | 5 April    | 30 March   | 8 April    | 24 February| 30 March  |
|         | Duration                  | 115        | 118       | 94         | 113       | 83        | 111       |
| Summer  | Onset                     | 31 May     | 30 May     | 16 May     | 27 May     | 19 April   | 23 May    |
|         | Cessation                 | 20 August  | 2 September| 16 August  | 3 September| 22 August  | 5 September|
|         | Central                   | 11 July    | 16 July    | 1 July     | 16 July    | 13 June    | 8 July    |
|         | Duration                  | 82         | 96         | 93         | 100       | 126       | 106       |
| Autumn  | Onset                     | 21 August  | 3 September| 17 August  | 4 September| 23 August  | 6 September|
|         | Cessation                 | 23 October | 3 November| 31 October | 5 November| 10 November| 1 November|
|         | Central                   | 23 September| 30 September| 16 September| 1 October| 7 October  | 3 October |
|         | Duration                  | 64         | 62         | 76         | 63        | 80        | 57        |

The first (1950–1979) and third (1970–1999) periods, winter lasted for 3.5 months; then it decreased to 3 months (similar to the 70-year analysis) during 1980–2009. During 1990–2019, winter was the shortest season, lasting 76 days between 11 November and 25 January. The central date of winter fluctuated between 26 December during 1950–1979; 2 January during 1980–2009; and 16–20 December during other periods. Winter began on 24 October in the 1950–1979 period, whereas in other periods (except 1990–2019) it started during the first week of November. Apart from 1970–1999 and 1990–2019, spring onsets, cessations and durations were close to each other’s in all overlapping periods; Spring began on 1–5 February, ended on 26–30 May, and lasted for 113–118 days. During 1970–1999, spring duration decreased to 94 days (11 February–15 May). Extra shortage (to 83 days: 26 January–18 April) was noticed during 1990–2019. Compared to 1950–2019, spring exhibited a shortage of 28 days in the last three decades.

Summer analysis showed extra prolongation compared to the astronomical definition. This prolongation was 3 days during 1960–1989, 7 days during 1980–2009. Whereas during 1990–2019, summer was the longest season at 126 days, between 19 April and 22 August. During 1970–1999, summer duration was identical to the astronomical definition, however summer started/ended 38 days earlier than the astronomical calendar. Only in the first period (1950–1979), summer duration receded the astronomical definition by 11 days. Summer central dates were identical (i.e., 16 July) during the 1960–1989 and 1980–2009 periods. In the first two periods (1950–1979 and 1960–1989), summer started on 30–31 May. Regarding autumn, the onsets and cessations varied between periods but were nearly the same during the second (1960–1989) and fourth (1980–2009) periods. Autumn started (ended) between 3 and 4 September (3–5 November) in the 1960–1989 and 1980–2009 periods, whereas it started (ended) between 17 and 23 August (23 October–10 November) in other periods. With the exception of 1970–1999 and 1990–2019, autumn duration was approximately 2 months. Compared to the whole seven decades analysis (1950–2019), autumn during the 1990–2019 period exhibited prolongation of 23 days.

Compared with the astronomical definition, seasons durations were most remarkable in autumn during 1960–1989 (a shortage of 27 days) and in summer during 1990–2019 (a prolongation of 33 days). Spring exceeded the astronomical definition by 25 days during 1960–1989. The variations in winter durations were smaller than in other seasons. During 1950–1979, winter exhibited prolongation of 14 days, compared with the astronomical definition. Winter onsets ranged between 24 October and 11 November in the five overlapping periods, presenting a remarkable earlier shift between 41–59 days than the astronomical winter onset. Autumn lasted 80 days during 1990–2019, that is, the largest duration in the five overlapping periods. The first four 30-year analyses (all except 1990–2019) suggest small changes in winter durations,
compared with the astronomical definition. The significant prolongation in summer duration (33 days) occurred during the 1990–2019 period. On the other hand, spring and autumn durations in the four overlapping periods had greater changes compared to the astronomical definition. The analyses showed that autumn declined in the first four overlapping periods, but a transition from winter to autumn during the last 30-year increased (decreased) autumn (winter) duration. Compared to the astronomical definition of seasons in the Northern Hemisphere, the analysis showed that winter’s duration, in 1990–2019, is being contracted at both ends and other seasons’ onsets advance the astronomical seasonal clock. These advances reached 55 days for spring, 65 days for summer, and 32 days for autumn. Autumn’s cessation advanced by 40 days. The latter finding justifies the overall decline in autumn during the 70-year period (32 days). Therefore, it can be concluded that the prolongation (shortage) in the duration of summer (winter) has occurred during the last three decades (1990–2019), which aligns with the recent warming and drying of the Arabian Peninsula.

3.3 | Changes in seasons characteristics over the last 30 years (1990–2019)

This section presents the changes in seasons characteristics during 1990–2019. Figure 7a shows the scree plot of the 12 climatic parameters used in this study. Outcomes showed that PC1 had a 62.78% variance, while PC2 and PC3 had a 26.82 and 5.6% variance, respectively. Taken together, the three PCs had a cumulative 95.24% variance, meaning that the other components could be ignored with a negligible loss of information. The contribution of the original parameters to PCs during 1990–2019 was similar to that during 1950–2019, suggesting that the studied parameters can represent the Arabian Peninsula climate during the last three decades. The k-mean cluster analysis was then performed using the three PCs. The optimal number of clusters was four, as Figure 7b shows, indicating that four seasons should be defined. Therefore, all dates in the year were categorized into four clusters based on their proximity to a corresponding cluster centroid.

The patterns found in the 12 climatic parameters for the central dates of the four seasons objectively defined during the 1990–2019 period are given in Figures 8–11. During the 1990–2019 period, the air temperature 2 m above the surface ranged between 9 and 32°C in all seasons except summer. The summer temperature reached 38°C over the Arabian Gulf, as shown in Figure 10a. Inconsiderable rates of precipitation were found in all seasons. Cloudiness ranged between 10 and 28.3% in winter and spring, and between 5 and 42.5% in summer and autumn. The highest percentage of cloud cover (42.5%) was found in autumn over the southwestern parts of the Arabian Peninsula. The 500 hPa temperature values were similar in winter and spring; they varied between −19 and −11.5°C in northern Arabian Peninsula and between −11.5 and −6.5°C in southern Arabian Peninsula. In summer and autumn, the 500 hPa temperature maps showed values between −11 and −4°C over the whole region. The highest value of 850 hPa temperature (≈ 33°C) was found in summer in the middle of Saudi Arabia. In contrast, the lowest value (≈7°C) was found in winter over northern Arabian Peninsula.

During 1990–2019, the 500 hPa geopotential heights were similar in winter and spring; both maps showed values between 5,700 and 5,800 m over northern Arabian Peninsula, and values between 5,800 and 5,880 m over southern Arabian Peninsula. The 500 hPa geopotential height was higher in summer and autumn than other seasons; it varied between 5,850 and 5,900 m over the whole area. Regarding the 1,000 hPa geopotential height, highest values (up to 171 m) were noticed in winter in northern Saudi Arabia and Kuwait, while lowest values (≈9 m) were observed in summer in southern Arabian Peninsula, particularly Oman and the United Arab Emirates. Compared to other regions in the Arabian Peninsula.
Peninsula, high quantities of precipitable water content (~30 kg m⁻²) were found in southwestern areas in winter imply the possibility for rainfall. During the last three decades, the Arabian Peninsula exhibited mean values of surface zonal wind between −6.7 and 0 m s⁻¹ in winter; −3.3 and 0 m s⁻¹ in spring and autumn; and values between 0 and 3.3 m s⁻¹ in summer. Meridional winds at 2 m exhibited values between −3 and 2.5 m s⁻¹ in winter, and values between −1.7 and 2.5 m s⁻¹ in spring and autumn. Compared to the 70-year analysis, the 1990–2019 period suggests additional prolongation in summer and shortage in winter. Regarding the onset dates, three seasons began earlier in the 1990–2019 period than they did in the 70-year period: spring (6 days), summer (34 days), and autumn (14 days). Between the two periods (1950–2019 and 1990–2019), the duration of summer increased by 19% and autumn duration increased by 40%, while the durations of winter and spring decreased by 20 and 34%, respectively. These shifts and changes correlate with the recent warming and drying of the Arabian Peninsula. Donat et al. (2014) studied the temporal changes in temperature and precipitation extremes in the Arab region during 1970–2010. Donat et al. (2014) concluded that the Arabian Peninsula summer is extending in length; the consecutive dry days (CDD) showed an evident trend toward drier conditions. Previous analyses during the
overlapping 30-year periods as well as comparing climatic parameters on the central dates of 1950–2019 and 1990–2019 periods supports the latter outcome (Figures 3–6 and 8–11). For example, near-surface air temperature in summer is higher during the 1990–2019 period than the 1950–2019 period. Also, spring and autumn precipitations were lower in the last 30-year period than in the 70-year period. In winter, the minimum precipitable water content was 13 kg/m² in the 70-year period but 5 kg/m² in the last 30-year analysis. The trends of temperature increase and precipitation decrease over the Arabian Peninsula during the last three decades support previous findings from Almazroui et al. (2020).

Almazroui et al. (2020) projected that, for the 21st century, the Arabian Peninsula annual temperature will increase at a rate of 0.63°C/decade, and the annual precipitation (averaged over Saudi Arabia) will decline at a rate of 6.3 mm/decade (both rates were statistically significant at the 99% level).

The last 30-year (1990–2019) analysis showed little higher values of 500 geopotential heights in all seasons than the 70-year analysis. While the maximum 500 hPa geopotential height in summer was 5,885 m during the 70-year period, it was 5,900 m during the 1990–2019 period. Additionally, the 1990–2019 period had higher values of geopotential heights in winter, spring, and

**FIGURE 9** The mean patterns of 12 climatic parameters used in this study for the central date of spring (24 February) during the period 1990–2019 [Colour figure can be viewed at wileyonlinelibrary.com]
summer than the whole 70-year period. These observations suggest that the circulation patterns have impacted the Arabian Peninsula climate during the last 30 years, consistent with previous studies (Donat et al., 2014; Attada et al., 2018; Attada et al., 2019; Almazroui and Hasanean, 2020).

4 | DISCUSSION

Literature discussing the evolution of seasons characteristics over the Arabian Peninsula is scarce, which makes comparing our results with previous work difficult. A comparison with studies conducted in the Northern Hemisphere and adjacent regions does show some agreement but also some variation. All analyses over the Arabian Peninsula showed an earlier start of spring, which agrees with studies across the Northern Hemisphere (Schwartz et al., 2006), central and northern Europe (Sparks and Menzel, 2002), and the United States (Zander et al., 2013; Allen and Sheridan, 2016). Similar to our findings, Allen and Sheridan (2016) concluded an earlier onset of summer in the United States during the 1948–2012 period. This study shows a decline in winter duration, which matches observed changes in Europe’s seasons from 1992 to 2002 (Sparks and Menzel, 2002). Additionally, Hochman et al. (2018) forecasted a longer summer and shorter winter through the 21st century in
the Eastern Mediterranean. The latter finding supports the current definition of seasons across the Arabian Peninsula. Over the last three decades, the duration of summer grew to 126 days, whereas the winter duration reduced to 76 days. In contrast, Allen and Sheridan (2016) concluded that autumn began earlier across the United States from 1948 to 2012. This study shows an earlier start of autumn as well. Autumn onset advanced by 18 days in the 70-year analysis and by 32 in the last 30-year analysis, compared to the astronomical definition. In the Eastern Mediterranean, Alpert et al. (2004a) found an equal duration (114 days) for both winter and summer during the second half of the 20th century. Our outcomes demonstrate that winter became more like summer over the last seven decades. This alteration (or shift from winter to summer) increases with time, with the duration of summer growing and the duration of winter declining.

The literature that redefines seasons characteristics in the Mediterranean has shown some inconsistencies. For instance, previous research in the Mediterranean (Alpert et al., 2004a; Kotsias et al., 2020) agreed on approximate durations of 4 months for winter and 2.5 months for autumn. However, these studies (Alpert et al., 2004a; Kotsias et al., 2020) disagreed on both the durations of the other seasons and autumn’s onset. Alpert et al. (2004a) concluded durations of 115 days for summer and 61 days for spring. Kotsias et al. (2020) found

![FIGURE 11 The mean patterns of 12 climatic parameters used in this study for the central date of autumn (7 October) during the 1990–2019 period](wileyonlinelibrary.com)
that summer and spring are slightly shorter than 3 months. Additionally, autumn’s onset varied by 14 days between the two studies. A possible explanation for the variations in season characterization is the use of different parameters leading to different results. Climatic parameters may unevenly represent phenomena that characterize seasons. Alpert et al. (2004a) adopted synoptic classification, whereas Kotsias et al. (2020) used several climatological parameters from the NCEP/NCAR reanalysis. Additionally, the inhomogeneity of the studied region’s climate may have caused inconsistencies. To illustrate, Reiser and Kutiel (2007) suggested including two distinguished regions, the southern region and the northern region, when defining the rainy season in the Mediterranean. This might also be applicable to the Arabian Peninsula. One could group the Arabian Peninsula into two regions because, when central date figures are analysed, southern areas—particularly Yemen and Oman—have different precipitation, specific humidity, and zonal wind parameters than northern areas.

Cassou and Cattiaux (2016) concluded that the disruption in Europe’s summer is partly attributed to anthropogenic forcings. They suggested that the decline in snow cover in Eastern Europe causes a reduction in the March east–west temperature gradient, which leads to a delay in winter’s onset and an earlier summer onset in Western Europe. Another study (Sparks and Menzel, 2002) linked the earlier commencement of Europe’s spring during the 1992–2002 period with temperature surge. The reason behind the changes in Arabian Peninsula’s seasons is unclear. The disruption of winter and summer durations might be related to the surge in air temperature and the decrease in precipitation, especially during the last three decades. Such an investigation is beyond the scope of this study, so further research is recommended.

5 | SUMMARY AND CONCLUSIONS

The presented study used climatic parameters from NCEP/NCAR reanalysis during 1950–2019 to objectively define seasons in the Arabian Peninsula. To categorize dates of the year with homogeneous climatic characteristics, PCA and CA were performed. The method was applied for the whole period (1950–2019) and five overlapping 30-year periods (1950–1979, 1960–1989, 1970–1999, 1980–2009, and 1990–2019). Results showed that the astronomical definition of seasons is inappropriate for the Arabian Peninsula. For the 70-year analysis (1950–2019), winter lasted for 3 months, whereas autumn was slightly shorter than 2 months. Spring and summer presented substantial changes from the astronomical definition, with earlier starts and remarkable prolongations (approximately 3.5 months). The 70-year analysis also showed that the autumn onset shifted by 18 days and autumn ended 49 days earlier than the astronomical definition. This led to an autumn decline and spring and summer prolongations. The length of spring (summer) exceeded the astronomical definition by 18 (13) days, as shown in Table 2. The last 30-year (1990–2019) analysis presented an extra prolongation of summer’s duration, prolongation of autumn’s duration and shortage of winter and spring durations compared to the total 70-year period. Over the last three decades, summer lasted over 4 months and winter lasted only 2.5 months. Meanwhile, spring and autumn lasted approximately 2.7 months. The earlier cessation of spring (about 2 months) contributed to summer’s prolongation.

Little has been done to investigate the evolution of the characteristics of seasons in the Arabian Peninsula. Hence, this work contributes significantly to our understanding of the changes in its climate’s seasonal clock. The presented definitions of seasons should be preferred for practical purposes. A longer summer and shorter winter lead to higher water requirements and severe water shortages. Since countries within the Arabian Peninsula depend on fossil aquifers to meet water demands—especially agricultural needs (Odhiambo, 2017; Ahmed et al., 2019)—potential aquifer depletion in the coming years becomes a greater threat. The long-term prolongation of the drought season might also lead to changes in the growing season and land cover. Linderholm (2006) estimated the prolongation in the growing season during the last century by 10–20 days. It remains an open question, thus, how water availability, the growing season, and ecosystems are affected by changes in the Arabian Peninsula’s seasons. It is also essential to explore the characteristics of seasons over longer periods. Over longer periods, date averages are expected to be more homogeneous, presenting a more accurate definition of seasons (Kotsias et al., 2020). Furthermore, the presented study does not directly consider the influence of prominent teleconnections patterns (e.g., North Atlantic Oscillation, Arctic Oscillation, East Atlantic/Western Russia, and ENSO). Additional studies may find that these phenomena impact seasonal climate variability in the Arabian Peninsula.

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CONFLICT OF INTEREST
The authors declare no conflict of interest.

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