This study investigates the dominant modes of surface air temperature (SAT) variability and associated circulation changes over the Arabian Peninsula (AP) during summer for the period 1979–2016 based on an empirical orthogonal function (EOF) analysis. The analysis results reveal that the first leading EOF mode is related to the weakening of the subtropical westerly jet stream, which may impact the AP temperature variability through the mid-latitude Rossby wave trains (successive troughs and ridges). This can be explained by the high correlation of the AP summer temperatures with the quasi-stationary mid-latitude/extratropical Eurasian Rossby wave train type patterns, which influences the air temperature variability by modulating the Asian Jets. Furthermore, the high AP SAT variability is also closely associated with strong middle to lower tropospheric descent (subsidence) anomalies, which cause warm temperature anomalies over this region.

KEYWORDS
Arabian Peninsula, mid-latitude Eurasian Rossby wave, summer surface air temperature

1 | INTRODUCTION

Air temperature is an important climatic parameter that affects the world socio-economy and is commonly employed to assess regional climate variations and climate change (e.g., Alkolibi, 2002; Walther et al., 2002). The Arabian Peninsula (AP) summers are among the hottest in the world, which impose an important strain on freshwater resources (World Bank, 2010; Al-Zahrani and Baig, 2011; Kaniewski et al., 2012; Odhiambo, 2017; Attada et al., 2018a). They are characterized by clear and hazy skies, with high temperatures during daytime and minimum temperatures during nighttime. The AP is further sensitive to the climate variability and is strongly vulnerable to climate change (Bannayan et al., 2010; Al-Zahrani and Baig, 2011; Kaniewski et al., 2012; Almazroui et al., 2013; Kunchala et al., 2018). Understanding the diverse impacts of summer temperatures is therefore important for developing adaptation strategies and actions in order to mitigate the consequences of climate change over the AP. The AP temperature variability has indeed an important implications on crop yield, water resources, and human health (e.g., Easterling et al., 2000; Alkolibi, 2002; Walther et al., 2002; Alghanmi and Moore, 2014, and references therein).

Despite experiencing serious environmental, agricultural, and water resource problems in the region, our knowledge about the AP temperature variations remains limited as compared to other regions (Almazroui, 2016). Several research groups only recently started investigating the temperature variability over the AP and adjoining regions. For instance, AlSarmi and Washington (2011; 2014) analyzed temperature data over the period 1980–2008 and suggested a clear signal of climate change in the region. Almazroui et al. (2012) reported a warming rate of 0.60 °C/decade based on annual mean air temperature data across Saudi Arabia. Athar (2012) also noted a significant rise in the summer extreme temperatures in recent decades, and Hasanean and Almazroui (2016)
reported an abrupt increase in surface air temperature (SAT) over the AP in the 1980s. Recently, Attada et al. (2018b) suggested that the AP SATs gradually increased, particularly during the last decades. Very few efforts have been, however, investigated the dynamical factors behind the variations of the AP temperatures, despite several studies suggesting that the AP SATs are controlled by various large-scale circulation patterns (Hasanean and Almazroui, 2016; Attada et al., 2018b).

Recent studies suggested that the mid-latitude/extratropical Eurasian Rossby wave is an important factor in describing the regional temperature variability during summer (e.g., Yadav, 2017). With the subtropical jet stream acting as a waveguide for Rossby waves (Branstator, 2002; Ding and Wang, 2005), successive troughs and ridges of Rossby waves travel along the jet stream and influence the characteristics of the Middle East regional climate (Yadav et al., 2009; Yadav, 2009a; 2009b). This study investigates the dominant modes of summer SAT variability and associated changes in circulation during the period 1979–2016. In the present work, we show that the Asian jet streams and mid-latitude/extratropical Eurasian Rossby wave train patterns are important modulators of the AP temperature variability.

2 | DATA AND METHODS

The European Centre for Medium Range Weather Forecast (ECMWF)-Interim (ERA-Interim) reanalysis (Dee et al., 2011), available at 0.75° spatial resolution over a 38-year period between 1979 and 2016, is used to investigate the summer AP SAT variability and associated changes in regional circulations. Summer seasons in the AP are from June to September (Almazroui et al., 2012). Monthly means of horizontal winds, vertical winds, sea level pressure (SLP), geopotential height (GPH), surface net solar radiation, and 2-m air temperature (2mT) variables are analyzed. To identify the leading spatio-temporal modes of variability, an empirical orthogonal function (EOF) analysis is performed on the linearly detrended ERA-Interim dataset (e.g., Yadav, 2009a; 2016; 2017; Chowdary et al., 2014; Chen et al., 2016). A correlation analysis is also performed at the 95% significance level, computed based on the Student’s t-distribution with (N−2) degrees of freedom, where N is the number of years in the record, to investigate significant relationships between the AP SATs and large-scale circulation patterns.

3 | RESULTS AND DISCUSSION

An EOF analysis is performed on the summer 2mT data to examine the dominant modes of variability. The leading EOF spatial mode of 2mT accounts for 33.44% of the total variance, as shown in Figure 1a. This represents the monopole pattern in temperature anomalies over the entire AP, excluding the tip of the southern AP. The largest local

![Image](https://example.com/image.png)

**FIGURE 1** The two leading EOF modes (a, b) of the 2mT anomalies for the period 1979–2016 and (c) corresponding air-temperature PCs. The EOFs were computed using the departures of the 2mT from their seasonal means for the summer season. Percentage of variance is shown at the top of (a, b).
loadings of the first EOF are found over the central to northern AP, with high positive loading over the north. The second EOF mode of 2mT explains 16.5% of the total variance (Figure 1b) and its spatial pattern is associated with positive loading over the eastern AP and Red Sea. It further exhibits opposite polarity over the northern and southern AP and a dipole-like pattern over the eastern and western AP regions. The time series of principal components (PCs) corresponding to the first and second EOF modes are shown in Figure 1c. These PCs represent a year-to-year (inter-annual) variation in summer 2mT anomalies over the AP, which are later considered for correlation coefficient (CC) analysis with different variables in order to investigate the main physical processes involved in the AP SAT variability. In this work, however, we focus on the first EOF mode as it captures a sizable percentage (33.44%) of the domain-integrated variance and describes the dominant AP SAT variability.

We present herein the CC maps computed between the monthly anomalies of various variables in the summer season and the first EOF mode of SAT. The results indicate that the PC of the first EOF (Figure 2a) time series and the 2mT anomalies are highly correlated (more than 0.8 CC), with 99.9% significance level, over the AP, East Asia, central Asia, the Middle East, and North Africa (MENA), the eastern Mediterranean (EM), and eastern Europe. The correlations are however not significant over the Indian region, except for the west coast (one of the monsoon rainfall zones) of India, Bay of Bengal, and northern Arabian Sea. This suggests that the first EOF mode is associated with the common warming of the AP, East Asia, central Asia, and MENA temperatures during summer.

The CC between SLP and the PC of the first EOF (Figure 2c) of the AP 2mT shows significantly negative CC (more than \(-0.7\)) over the MENA and EM regions, including the Red Sea. A significant positive correlation of 0.9 between AP 2mT and SLP is also found over Iran. The positive surface pressure anomaly over Iran and the negative pressure anomaly over the AP create a southerly wind anomaly over the AP, which weakens the northerly winds (Zarrin et al., 2011; Giannakopoulou and Touni, 2012; Yu et al., 2016). This prevailing southerly wind anomaly blowing from the warm Indian Ocean advects warm temperatures towards the AP. It is further important to emphasize that the local factors (such as elevation and vicinity to the Arabian Gulf) over Iran induces thermally driven circulation from the mountains, which also plays an important role in modulating the AP surface temperatures. This clearly indicates that the inter-annual variations of the AP SATs are influenced by the regional pressure patterns.

The CC between zonal winds at 200 hPa and PC of the first EOF of the AP 2mT (Figure 2b, shaded) shows a significant negative CC all along the Asian subtropical westerly jet stream, from the EM to central Asia and the Bay of Bengal. A significant positive CC (0.7) is also noticeable along
the polar jet stream region from northern Europe to Russia, Iran, and Afghanistan. This indicates a weakening of the Asian subtropical westerly jet stream and intensification of the polar and tropical easterly jet streams. These modulations in the circulations play an important role in the AP temperature variability during summer. The weakening of the subtropical westerly jet stream leads to a reduction in the upper tropospheric transients over the Eurasian region, which reduces the mid-latitude/extratropical disturbances (Yadav, 2016). This reduces the tropical/extratropical mixing and thereby increases the temperature during summer. We further plotted the CC between PC of the first EOF mode and the upper level GPH at 200 hPa (Figure 2d) to infer the large-scale circulation influence of the latter on the 2mT of the AP during summer. One can see that 2mT is positively correlated with the upper winds over the wide, zonally elongated regions of the northern AP, Iran, EM, the Black Sea, northern Russia, and the Tibetan region. The CC between PC of the first EOF of AP 2mT and the upper troposphere (200 hPa) meridional winds (Figure 3a) exhibit a significant positive correlation over eastern Europe, negative correlation over the Caspian Sea, positive correlations over the Kazakhstan regions, and a significant negative correlation over Sudan. These successive positive, negative and positive anomalies resemble a Rossby wave train pattern and play an important role in the AP SAT variability during the summer. In summary, the mid-latitude tropospheric Rossby wave train type pattern influences the AP SATs by modulating the upper tropospheric Asian jet stream during the summer. The Asian jet stream and Eurasian wave train impose a surface pressure dipole anomaly over the AP and Iran, and consequently influence the AP SAT variability (Yadav, 2017).

Surface heat lows, characterized by winds converging at the surface level and diverging at mid-level, are common over the Middle East desert regions during summer (Blake et al., 1983). These winds meet in the middle troposphere (at 500 hPa level) and form a mid-tropospheric anticyclone, which is an important factor in the AP temperature variability (Blake et al., 1983). We thus also correlated the mid-level (500 hPa) GPH with PC of the first EOF of 2mT, as shown in Figure 3b. Positive GPH anomalies were found over the AP, Egypt, the Black Sea, the Caspian Sea, northern India, and the Indian subcontinent, which is consistent with Figure 2d. This positive GPH anomaly over the AP is closely associated with the warm temperature anomalies over the AP during summer. We further computed correlations with solar radiation, which is also an important driver of temperature variations. The net solar radiation is negatively correlated with the PC of the first EOF of 2mT over the AP, eastern Africa, and western European regions (Figure 3c) during summer as a result of high surface temperatures over the desert regions, which lead to net loss of radiation over the AP. The correlations between the PC of the first EOF of 2mT and the downward/upward shortwave radiations (not shown) are also negative. The low humidity and lack of clouds over the AP desert atmosphere allow a

FIGURE 3  Same as Figure 2 except for (a) upper level (200 hPa) meridional winds (m/s); (b) middle level (500 hPa) GPH (gpm), and (c) net short wave radiation (W/m²)
substantial part of the incident solar radiation to reach the Earth’s surface. A relatively large percentage of this radiation, due to the high albedo, is reflected back to the top of the atmosphere (e.g., Blake et al., 1983). Since the summer surface temperatures over the AP are higher, this results in net loss of radiation into the atmosphere. A similar negative surface radiative forcing was also reported by Islam and Almazroui (2012). It is found that the correlations between the PC of the first EOF of 2mT and the downward/upward longwave radiations are positive, which are also contributing the AP temperature variability during summer.

Figure 4 plots a vertical cross section of GPH, temperature, and vertical velocity averaged over the AP during summer in the troposphere (1,000–100 hPa). GPH increases with height, as expected, while the mean temperature decreases with height. The rate of decrease in temperature from the surface to the 750 hPa level is relatively lower than that of the above layers, suggesting the presence of an inversion layer at around 750 hPa level. In general, the summer SAT is high, owing to strong summer time solar insolation (being a cloud-free region), strong adiabatic heating (large-scale subsidence), and low thermal inertia of the dry desert soil (Yadav, 2016; 2017; Attada et al., 2018b). The vertical profile of the mean vertical velocity displayed an ascent from the surface to the lower troposphere (i.e., 700 hPa) due to surface heating, and a descent throughout the middle and upper troposphere. The shallow ascent near the surface and middle to upper troposphere descent produces the inversion layer at the 700 hPa level. The descent is maximal in the mid-troposphere (500–300 hPa levels).

The CC of PC of the first EOF of AP 2mT (PC1) with vertical cross sections of temperature, GPH, and vertical velocity over the AP region is shown in Figure 4b. The vertical profile of CC between PC1 and the GPH (Figure 4b, black curve) outlines a significant positive correlation from the upper to middle troposphere (i.e., 800–100 hPa) and negative correlation near the surface (i.e., 1,000–800 hPa). The CCs are maximal in the mid-troposphere, between 600 and 400 hPa levels. This suggests the accumulation of masses in the upper troposphere due to positive GPH anomaly over the AP, as observed in Figure 2d, associated with the mid-latitude/extratropical Eurasian wave, propagating from northwest Europe to the AP. The CC plot for temperature (Figure 4b, red curve) shows a significant positive temperature anomaly from the 1,000–500 hPa levels. The CCs are maximal from the 1,000–700 hPa levels, negative at the 500 hPa level, positive from the 550–200 hPa levels, and become negative again between the 150 and 100 hPa levels. The higher temperature anomaly in the lower troposphere raised the inversion layer up to the middle troposphere, which is represented by the negative temperature anomaly at 500 hPa. The vertical profile of the vertical velocity CC (Figure 4b, blue curve) shows a descent anomaly from the surface to the 400 hPa level, with a maximum at the 700 hPa level.

To further demonstrate the contribution of the Rossby waves to the AP temperature variability, the Rossby wave activity flux at 250-hPa pressure level, as defined by Takaya and Nakamura (2001), was computed for summer. The results plotted in Figure 5 support the existence and propagation of Rossby waves in the basic flow. These waves are cascading downstream from the EM towards the AP region, suggesting the influence of the Eurasian Rossby wave train on the AP surface temperature variability.

In summary, a plausible mechanism for the summer AP temperature variability is the strong positive GPH anomaly.

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**FIGURE 4** (a) Summer climatological vertical profile for GPH ($\times10^4$ gpm, black), temperature ($^\circ$C, red), and vertical velocity (m/s, blue). (b) Vertical profiles of the CCs between PC1 of AP 2mT and GPH, temperature, and vertical velocities during summer.
due to extratropical Eurasian Rossby waves) in the upper to middle troposphere, which accumulates a substantial amount of atmospheric mass. The climatological background of strong tropospheric subsidence in the upper to the middle troposphere causes the accumulated mass to penetrate to the middle to lower troposphere. This increases the tropospheric temperature as a consequence of strong adiabatic heating. The downward penetration of the accumulated atmospheric mass and the cloud-free atmosphere of the AP amplify the surface temperature of the low thermal inertia soil of the AP due to strong adiabatic heating and intense solar radiation. This increased temperature anomaly in the lower troposphere lifts the inversion layer upward (the inversion layer is prominent at the 500 hPa level). This causes a reduction in atmospheric mass at the lower level, and thus a significant negative GPH anomaly near the surface (i.e., negative surface pressure anomaly). It further intensifies the surface shallow low-pressure area over the AP, which increases the vertical motions in the lower troposphere.

4 | SUMMARY

We investigated the dominant modes of summer SAT variability and associated circulation changes over the AP during the period 1979–2016. The leading modes of summer 2mT were associated with different regimes of the atmospheric circulation patterns. The first leading EOF mode (explained 33.44% of total variance) was related to the weakening of the subtropical westerly jet stream. The correlations of the AP 2mT with the upper level zonal winds during summer suggested that the weakening of the Asian subtropical westerly jet stream and the zonal movement of upper tropospheric Rossby wave train types can be attributed to temperature variations over the AP. These waves originate from the EM and propagate downward to influence the AP SATs. It was also found that the AP SATs had significant close relationships with the Iran temperatures.

The extratropical Eurasian Rossby waves caused the positive GPH anomalies in the upper to middle troposphere, which accumulated substantial amounts of atmospheric mass. The tropospheric subsidence enhances the potential and internal energy (Yadav, 2017). The strong adiabatic heating due to the mid-tropospheric descent further caused the positive SAT anomalies over the AP. This study revealed a significant relation between the AP summer temperature variability and the large-scale circulations.

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