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Features of climatic temperature over Saudi Arabia: A Review

Hosny M. Hasanean* and **Abdulhaleem H. Labban**

Department of Meteorology, King Abdulaziz University,
P.O. Box 80234, Jeddah, Saudi Arabia

**Corresponding Author e-mail: hhasanean@kau.edu.sa*

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Abstract—The climate around the world including Saudi Arabia has been fluctuating from cold to warm during different periods. The climate of the earlier period of the 650 ka BP was warmer than the present time in Saudi Arabia due to greenhouse gases in the atmosphere. The current climate of Saudi Arabia is arid to semi-arid with different climate classes. The seasonal surface air temperatures (SATs) are high in the central and northern regions compared to the southern region. The summer of Saudi Arabia is the warmest around the globe with the exception of the coastal region. Due to different air masses that invade the regions of Saudi Arabia, there are different SATs in different seasons. Depending upon seasonal and annual basis, the frequency of the extreme cold SAT is less than the extreme warm SAT.

The circulation pattern of high and low pressures plays an important role in the climatic SAT of Saudi Arabia. The coldest year is associated with the Siberian high-pressure during winter and early spring, especially in the central and northern areas, while the warmest year is related to the Indian monsoon low-pressure during summer and early autumn especially on the northeastern parts, majority of the east coast, and central regions of Saudi Arabia. On the other hand, the Icelandic low pressure extended to the southern region causes cooling air over the area, especially, the northern part of Saudi Arabia, while the Sudan low-pressure causes warming and moisture from the southern and southwestern regions in the winter season. The synoptic situation in the spring season is almost similar to the autumn season. During the spring and autumn seasons, the synoptic circulation over Saudi Arabia is Siberian high-pressure from the east, subtropical high-pressure from the west, Mediterranean depression from the north, and Sudan low and/or Asian monsoon low from south.

Key-words: surface air temperature, Saudi Arabia, climate past and present, synoptic circulation, Siberian high pressure, subtropical high pressure, Icelandic low, Sudan monsoon low

1. Introduction

Saudi Arabia is characterized by complex topographical features and occupies nearly eighty percent of the Arabian Peninsula, which is approximately 2,250,000 km^2. Saudi Arabia extends from 15.5°N to 32.5°N in latitude and from 32°E to 55°E in longitude (*Fig. 1*). The country is distinguished by different climatic regions because of high spatial and temporal SATs variability. Moreover, the distribution of the observed SATs dataset is also distinguished by high inter-annual variability (*Almazroui et al.,* 2009).

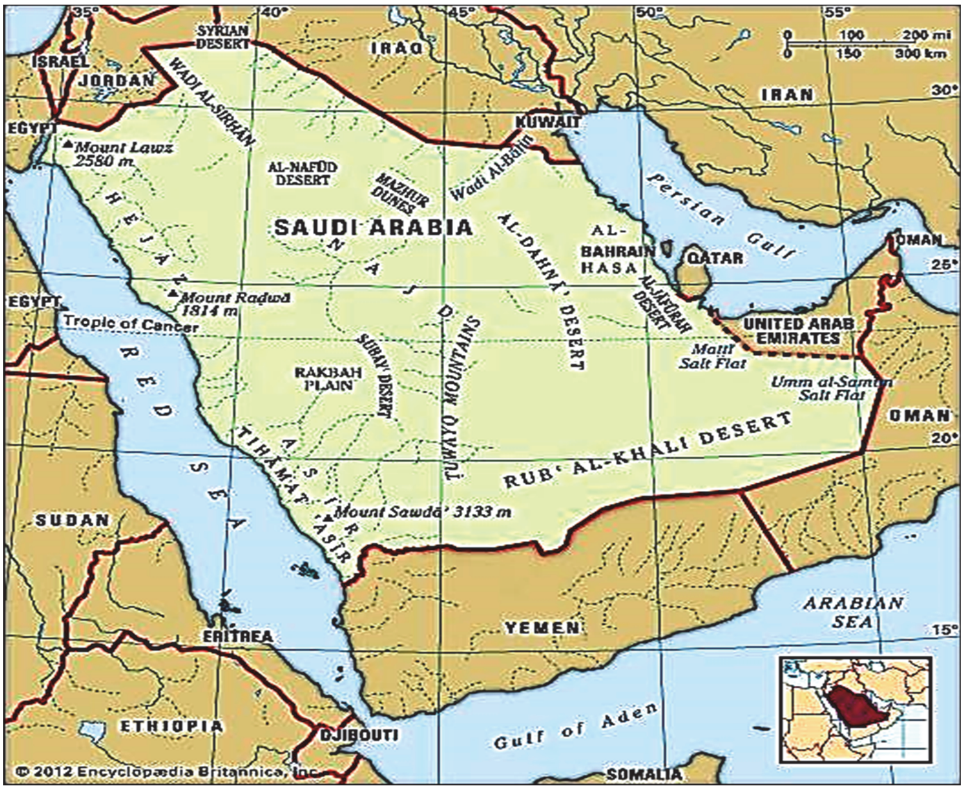

Fig. 1. Location of Saudi Arabia

Surface air temperature over Saudi Arabia in the past

Between 870 Ma and at the end of the Precambrian time (roughly around ~542 Ma), the structure of the Arabian-Nubian Shield and the East African Orogen developed (*Stern et al.,* 2006; *Kotwicki et al.,* 2007; *Kotwicki* and *Al Sulaimani,* 2009), and the main structural and tectonic events shaped the area in the late Cretaceous. The Arabian Peninsula, as the Arabian Plate, stayed in continuous contact with Africa up to the formation of the Red Sea rift in the late Tertiary era. More than 2 Ma ago, the great Al-Rub Al-Khali desert began to form, with its climate oscillating from hyper-arid to temperate.

From the time series of atmospheric trace gases and aerosols for the period from about 650 ka BP to the present (*Jansen et al.,* 2007), one can find that earlier periods were warmer than the present. The world climate was cold and dry by 150,000 BCE and started to increase by 140,000 BCE (*Edmiston,* 2007). By 130,000 BCE, the climate was almost analogous to the current era of the world, while it remained cold and dry during 120,000 BCE. At the end of the initial cooling (110,000 BCE), temperature changed dramatically. However, the climate remained stable for thousands of years. The climate became slightly warmer around sixty thousand years ago followed by a long phase of climate oscillation. Around thirty thousand years ago, the climate returned to cooling, which is termed as late-glacial cold stage, and extended to the successive twenty-one thousand and seventeen thousand years. At the beginning of the Holocene phase (9500 BCE), the cold period ended abruptly, while warming continued to prevail gradually. Similarly, there were cold and dry periods for the next thousand years, although significant areas of the world were under high moisture and warmer conditions. Therefore, the Arabian and Saharan deserts disappeared with most of their area covering vegetation. During the Holocene Climate Optimum (HCO), which is the period between nine thousand and five thousand BCE, the Sahara regions were greatly influenced by increased rainfall. However, Eastern Sahara began to return desert during 5300 BCE due to decrease in rainfall.

McClure (2007) established the presence of the human population in the Empty Quarter with the existence of hand axes that have been found from more than 100 ka on the fringes of the region. However, the origin of the human population in the region has not been firmly established yet. *Majewski et al.,* (2004) categorized six periods of significant rapid climate change, that is, 9,000–8,000, 6,000–5,000, 4,200–3,800, 3,500–500, 1,200–1,000, and 600–150 BP. Changes in atmospheric circulation, tropical aridity, and polar cooling are the most frequent occurrences of climate change events in these global records, even though polar cooling together with rise in the moisture in some areas of the tropics happened in the most recent period from 600 to 150 BP. Numerous eras correspond with the main disturbances of civilization, showing the significance of Holocene climate changes on humans. Across the Pleistocene/Holocene boundary, the Arabian Peninsula climate changed from temperate to arid. *Edmiston* (2007) estimated that a 200-year cooling period during 8,000 BP had reduced the amount of rainfall by 30 percent in the Arabian Peninsula.

Kotwicki and *Al Sulaimani* (2009) found four successive ice ages, alternating with hot periods in the Pleistocene due to climate change. Throughout the greatest recent glaciations, most of the earth's water insulated in the ice sheets of North America and Asia, and the sea level declined by approximately 125 m, uncovering the bottom of the Arabian Gulf (mean depth about 35 m). The Tigris-Euphrates glacial era stream extended from Shatt-al-Arab to the Strait of Hormuz into the Arabian Sea.

An overview: present climates of Saudi Arabia

In Saudi Arabia, the climate varies from place to place due to the changes in dynamics of serious weather and climatic elements. Climatic elements are liable for provincial dispersal because of the influences of radiation, atmospheric circulation cells, different water and landmasses, latitude, winds, altitude, and air masses. Climate controls in combinations and interactions modify the short-term averages of temperature and precipitation giving special climate zones (*Masatoshi and Urushibara,* 1981). The leading elements controlling SAT over Saudi Arabia are latitude and height. SATs are highly seasonal dependent, with being relatively cool in the period from December to February and warm in the period from June to September. However, the annual variability in temperature is very low in contrast to variability in annual rainfall amount.

Most of Saudi Arabia lies in the tropics (15.5°N - 32.5°N; 32°E - 55°E). It is a huge area that lies between the vast continental landmasses of Africa and Asia. The vast area of the country (80% of the Arabian Peninsula) and its complex topography encompass significant climate variations in space and time. Saudi Arabia is one of the warmest countries in the world except for its coastal regions during the summer season. Saudi Arabia is among the few countries in the globe, where SAT during the summer season exceeds 50 °C. According to *Krishna* (2014), the SAT is in between 27 °C to 43 °C during the summer season over the country except for the coastal regions, where it lies between 27 °C to 38 °C. SAT over Saudi Arabia increases gradually from north to south (*Almazroui*, 2019). Moreover, highlands play an important role in the local climate in the country.

The Saudi Arabian climate is known for its deserts except for the mountainous areas in the southwest. It is characterized by warming in the daytime and sudden cooling in the nighttime. Warm SATs take place in the north of the Tropic of Cancer as well as in the ultimate northern and interior regions of Saudi Arabia. However, the mountains in the southwestern region experience temperate temperatures. Away from the topographical effect, the climate of Saudi Arabia is also influenced by the latitude, tropical winds, vicinity to the sea, elevations, etc.

The two of the most famous world climate classification have been drawn by *Köppen* and *Geiger* (1928)*, Koppen* (1936), and *Troll* and *Paffen* (1980). The world map of the Köppen-Geiger climate classification has been updated by *Peel et al.* (2007). However, the Arabian climates have been classified by both authors on a broad scale without consideration of regional differences. One reason associated with the broad-scale climate classification of the Arabian Peninsula is the limited number of weather stations operated at that time. According to the *Köppen* and *Geiger* (1928) classification, the climate of the whole Arabian Peninsula is 'desert climate' except for the mountainous regions in the southwest of Saudi Arabia. Also, they classified the climate of Saudi Arabia as BWh climate; a dry desert climate with an average SAT above 18°C, whereas *Köppen* (1936) used different climate classes for the Arabian Peninsula. *Walter* and *Lieth* (1967), *Muller* (1982), and *Moore* (1986) provided brief and sound climatological information on the Arabian Peninsula. They showed a wide spectrum of climatic change in the Arabian Peninsula, from the ice in the Asir mountain to the great humidity of the Arabian Gulf, and from the rising heat of Al-Rub Al Khali to the monsoon rains in the Qari Province in Dhofar.

The climate of Saudi Arabia is described as semi-arid and arid with spatiotemporal variations of temperature and rainfall noticed across the region (*Almazroui et al.,* 2012a, *Almazroui,* 2013). *Almazroui et al.* (2012a) and *Almazroui et al.* (2012b) demonstrated that air temperature is low in the northwestern and southwestern highlands regions of the country and high in the central area towards the Arabian Gulf and western coastal areas along the Red Sea. Additionally, the seasonal mean temperature variability is high in the northern and central regions compared to the south of the country (*Almazroui et al.,* 2012a). Except for the province of Asir on the western coast, Saudi Arabia has a desert climate characterized by extreme heat during the day, an abrupt drop in temperature at night, and very low annual rainfall. Because of the influence of a subtropical high-pressure system, there is significant variation in temperature and humidity in the country. The two major distinctions in the climate of Saudi Arabia can be felt between the coastal part and the interior regions.

Almazroui et al. (2014) used the principal component and correlation methods to regionalize the climate of Saudi Arabia into several homogenous groups. They selected twenty-seven stations across the country for regionalization of climate during a period of twenty-six years (1985 to 2010). They identified five groups: group “A” for the northern region, group “B” for the Red Sea coast, group “C” for the interior region, group “D” for the highlands, and group “E” for the southern region. Moreover, the interannual variability and the degree of seasonality are the same for each climatic group.

2. *Air masses that affect the surface air temperature over Saudi Arabia*

The movement and transformation of air masses, and interactions between air masses along the fronts give the regional climate of Saudi Arabia. So, the climate of the country can be clarified in terms of regional air masses. According to *Abdullah* and *Al-Mazroui* (1998), four different types of air mass (*Fig. 2*) influence the weather elements in Saudi Arabia. *Fig. 2* reveals the source and direction of these air masses.

1. The polar continental air mass affects the region during the winter season from December to February, sometimes to mid-March. The domination of the Siberian high in central Asia is responsible for this effect. Polar continental air masses are cold (-35 °C to -20 °C), very stable with strong temperature inversions, and dry. They extend through the Siberian high

pressure and dominate the weather of the entire continent. Generally, polar continental air masses generate cold air and clear sky weather.

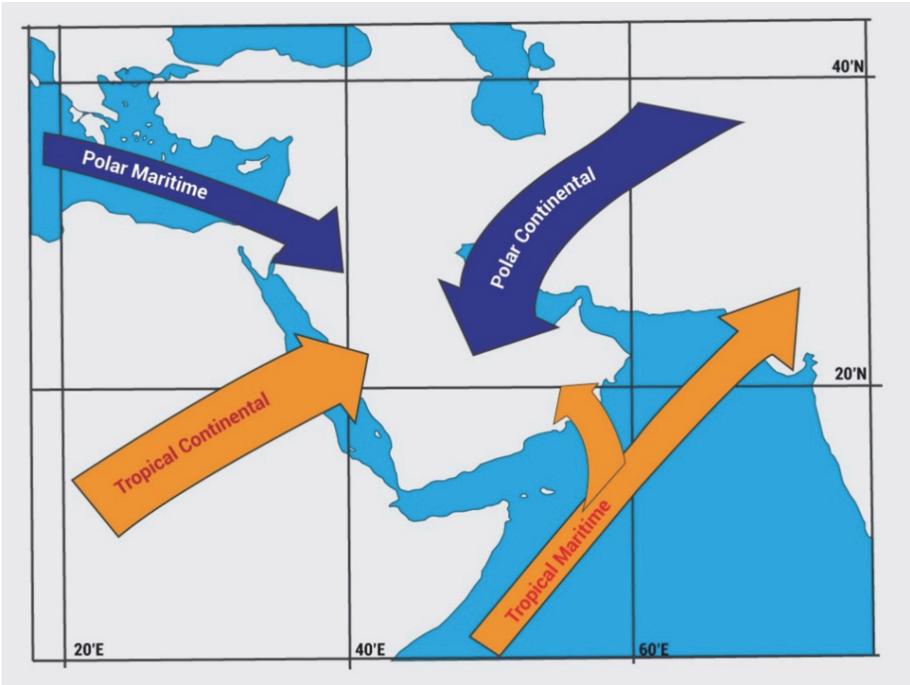

Fig. 2. Air masses influencing the weather elements in the Saudi Arabian.

2. Occasionally, Saudi Arabia is influenced by polar maritime air masses coming from the North Atlantic. It reaches the area because of mid-latitude depressions that move from the west during the winter season. Polar maritime air masses are cool (0 °C to 10 °C), basically conditionally stable, and moist.
3. The tropical continental air mass affects Saudi Arabia in the spring and early summer seasons. This air mass allows the region to become a stable high-pressure zone and a source of tropical continental air. This air mass is hot and dry (>45 °C) and can create strong heating on the surface and dusty weather system (*Fisher* and *Membery,* 1998). In general, in southwestern Asia, summer is very hot, the temperature ranges from 30 °C to 42 °C. A tropical continental air mass is conditionally stable, dusty, and holds moisture. Tropical continental air mass flows north and northwest during the summer season in western Asia. When the Indian monsoon system moves toward the region of the Arabian Peninsula, certain activities occur in summer, particularly in southwestern Saudi Arabia. On the other hand, its influence is limited by the strong tropical continental air mass, which prevails over Saudi Arabia at the time. Overall, the southwestern region has

a lower temperature because of elevation, whereas the other areas are influenced by the tropical air mass during the spring, summer, and autumn seasons (*Tarawneh* and *Chowdhury,* 2018).

4. The tropical maritime air mass invades from the north of the Indian Ocean and the Arabian Sea in the summer season. It impacts principally the southwestern region of Saudi Arabia and produces hot and humid air (*Fisher* and *Membery,* 1998; *Abdullah* and *Al-Mazroui,* 1998). Initially, tropical maritime air masses are hot, conditionally stable, and very moist.

3. Climatology of the surface air temperature in different seasons

The SAT over Saudi Arabia is influenced by many factors including mountain barriers, altitude above sea level, ocean currents, solar radiation, and pressure cells. A cooling trend from south to north in the region of Saudi Arabia is found due to the impact of the cold continental air masses during the winter season. The SAT is low (<15 °C) over the northern, moderate (15–20 °C) over the central and western, and high (up to 20–25 °C) over the southeastern parts of Saudi Arabia during the winter season. Therefore, the climate of the region during the winter season has three different climate zones. Due to the impact of the cyclones in the Mediterranean region, northern Saudi Arabia is cooler than the other regions during the winter season, while southern Saudi Arabia is much warmer due to less precipitation. Moreover, the SAT in the southwestern regions, which are associated with the local topography, is lesser than those in the southeastern regions of Saudi Arabia (*Langodan et al.,* 2014; *Viswanadhapalli et al.,* 2017; *Attada et al.,* 2019). In the winter season, the SAT rarely goes below 0 °C, however, the virtual absence of moisture and the high wind-chill factor create a somewhat cold atmosphere.

During spring, in general, the SAT increases over Saudi Arabia; however, it increases faster in the northern region (between 20 and 25 °C), while the eastern desert region is warmer with SAT between 25 and 27 °C (*Khan* and *Alghafari* 2018; *Attada et al.,* 2019). The spring season is sometimes called the cool moderate season of the post-winter and the summer season (*Khan* and *Alghafari,* 2018).

In the summer season, the SAT becomes intense quickly after sunrise up to sunset, then suddenly becomes cool at night. In early summer (May and June), the distribution of SAT is steadier across Saudi Arabia. It is observed above 35 °C in the eastern region and around 25 °C in the southern part of Saudi Arabia, see *Attada et al.* (2019). The average SAT in the summer season is around 45°C, except for an unusual increase of around 54 °C especially over desert areas due to strong descent motion (*Babu* 2016; *Hasanean* and *Almazroui,* 2017). According to the study of *Rodwell* and *Hoskins* (1996, 2001), this descent motion is related to the mechanism of the desert-monsoon over the region and stronger summer insolation. Additionally, *El Kenawy et al.* (2014, 2016) exhibited heating during the summer season with thermal lows.

In the autumn season, SATs over Saudi Arabia is between 20 to 25 °C. Moreover, SAT remains below 25 °C in the western and northwestern regions of Saudi Arabia, while the highest values of SATs are found in the eastern regions of (*Attada et al.,* 2019). In the spring and autumn, the SAT is moderate with mean temperatures approximately 29 °C.

The Climate Research Unit (CRU) is a Global Climate Dataset, available through the IPCC DDC, consists of a multi-variate 0.5º latitude by 0.5º longitude resolution mean monthly climatology for global land areas, excluding Antarctica. The CRU TS3.1 dataset derived from the gridded climate datasets, interpolated using the original information from the stations since 1901. In the interpolation records, the anomaly with respect to the average for the period 1961–1990 is calculated. The anomaly is interpolated using thin-plate splines as a function of latitude/longitude. The CRU dataset gridded values are obtained by applying a smooth fitting (in 3D space) to the available surface station observations (*New et al*., 2000).

Almazroui et al., (2012b) studied the spatial distribution of the mean average temperature for the period 1979–2009 for the wet season (from November to April) and dry season (from May to October) by using ground-based meteorological data measured at the meteorological stations located in Saudi Arabia and Climate Research Unit (CRU) data.

They found that the mean temperature is low (below 15 °C) in the northern part of Saudi Arabia for the wet season. In addition, low temperatures in the southwestern coastal region of Saudi Arabia are also found. However, the highest temperature (> 24 °C) is found over the west coast region. On the other hand, during the dry season, mean temperature over Saudi Arabia is high (*Almazroui et al.,* 2012b). The highest temperature ranges from 33–36 °C from inland of the Arabian Gulf to the center of the country. Low-temperature regions appear over the northwestern and southwestern zones. However, the lowest temperature (>24 °C) is observed over the southwestern regions of Saudi Arabia.

The distribution pattern of the wet season averaged maximum temperature for the period 1979–2009 is similar to the mean temperature pattern (*Almazroui et al.,* 2012b). The highest maximum temperature over Saudi Arabia is observed along the Red Sea coast (> 30 °C). The mean maximum temperature over Al-Rub Al-Khali is between 27 °C and 30 °C. However, during the dry season, the highest maximum temperature (>42 °C) is found in the northeast region of the country. In the dry season, the maximum heat (temperature < 42 °C) is observed over northern Saudi Arabia. The minimum heat (temperature > 27 °C) is found over southwestern Yemen. At most stations of Saudi Arabia, high temperatures are also observed.

Almazroui et al., (2012b) studied average minimum temperature of the wet and dry seasons using the CRU and stations dataset for the study period (1979–2009). The minimum temperature (> 9 °C) is investigated over each of the northwestern and southwestern areas of Saudi Arabia, Iran, Iraq, Jordan, and Egypt. The minimum temperature over the west coast and Al-Rub Al-Khali of Saudi Arabia is around 18 °C and 24 °C, respectively. The results arising from the spatial distribution of the minimum temperature are supported by the results arising from the CRU dataset (*Almazroui et al.,* 2012b). The highest value of the average minimum temperature for the dry season (> 33 °C) is found in a narrow part of the eastern part of Saudi Arabia, while the lowest value (<18 °C) is evident over the southwestern part of Saudi Arabia extending to the western region of Yemen. For the minimum temperature during the dry season, the lower temperature is investigated over the northern parts of Saudi Arabia. The observed datasets confirm the pattern distribution of the Climate Research Unit datasets. In comparison to the wet season, the region of high temperature is transmitted to the north.

4. Annual surface air temperature climatology

Temperature is an important element for any vulnerability evaluation in a climate change, and its analysis depends on the variations in its mean, maximum, and minimum values. Saudi Arabia is a warm country with a mean annual temperature of exceedingly more than 30 °C in some areas. *Almazroui et al.* (2012a) and *Attada et al.* (2019), studied the climatological behavior of the mean, minimum, and maximum annual temperatures over Saudi Arabia. They used the gridded dataset from CRU and the observed datasets retrieved from various ground stations in different parts of Saudi Arabia. From the gridded CRU dataset for the period from 1979 to 2009, the highest mean annual temperature of the SAT is noticed over the Al-Rub Al-Khali (around 27–30 °C), and southwest of Saudi Arabia mainly along the Red Sea coast (*Almazroui et al.,* 2012a). Moreover, the mean annual SAT over most regions of Saudi Arabia is between 24–30 °C. Whereas, in the northern part of Saudi Arabia, the mean annual SAT is lower than 21 °C. The study of *Almazroui et al.,* (2012a) showed that the mean annual temperature over most areas in Saudi Arabia is around 20 °C.

Almazroui et al., (2012a) used CRU gridded dataset as well as the ground-based observational dataset to study the annual mean minimum temperature pattern from the period 1979 to 2009 over Saudi Arabia. The low value of temperature from 6 to 15 °C is observed over the northwestern and southwestern regions of Saudi Arabia. However, a relatively higher temperature of 21–24 °C over the southeastern regions, mainly over Al-Rub Al-Khali is observed. The south-eastern regions are the highest temperature zones in the country. It is also noted that the results of the ground-based observational data are like those of the gridded CRU data.

The annual mean maximum temperature pattern for Saudi Arabia averaged over the period from 1979 to 2009 is studied by *Almazroui et al.* (2012a) using both the CRU and ground-based observational datasets. The maximum value of temperature peaks observed in the middle of the country is due to the influence of the land-sea contrast. Moreover, the highest temperature (33–36 °C) over the southwestern region of Saudi Arabia is also observed. On the other hand, a slightly lower temperature is found along the Red Sea coast. A moderate temperature between 27 °C and 33 °C is found in most of Saudi Arabia. Once again, the results of the ground-based observational data are similar to those of the gridded CRU data. *Almazroui et al.* (2012a) concluded that the gridded CRU datasets of the annual mean, minimum, and maximum temperature over Saudi Arabia fairly represent the climatological features of Saudi Arabia, which is similar to the observed dataset.

5. Climate extremes of temperature over Saudi Arabia

Climatic extreme events may have main influences on the economy, ecosystems, society, and human health. Climatic extreme events drive natural systems compared to average climate (*Parmesan et al.,* 2000). At the global scale, the anthropogenic influences may have led to warming of extreme daily minimum and maximum temperatures and contributed to the intensification of extreme precipitation (*Handmer et al.,* 2012). Moreover, *Peterson et al.* (2012) illustrated how anthropogenic climatic change is changing the probability of occurrence of extreme events. Extreme cold and hot temperature can have huge impact on society. Seasonal changes in temperature both extreme cold and/or hot can have serious negative impacts on farming, tourism, etc. Prominently, what is ‘normal for one area may be extreme for another area that is less well adapted to such temperatures.

Over the northwestern area of Saudi Arabia, the extreme temperature is in overall agreement with the prognostic warming over the Mediterranean region (*UNFCCC,* 2011). During the summer of 2010, extreme warming influenced the Saudi Arabia region, with outstanding readings of 52.0 °C at Jeddah. In the second report of the UNFCCC, one can conclude that the anomalies of the annual mean temperature of the coolest year (1992) are found at all stations. All anomalies are negative ranging from -1.8 ° to -0.6 °C, in which extreme cooling occurred over the central and northern regions of Saudi Arabia in association with a deep invasion of the Siberian high pressure in winter and early spring. On the other hand, anomalies of the annual mean temperature of the warmest year (1999) are found at all stations. All anomalies are positive ranging from 1.5 ºC to 0.2 ºC, in which the extreme warming occurred over the central part and most of the eastern coasts and northeastern regions of Saudi Arabia in association with an extension of the Indian monsoon in the summer and early autumn.

Extreme heat and cold waves arise from any changes/variations in climate (*Kotwicki* and *Al Sulaimani,* 2009). Any variations and/or changes in climate cause variations and/or changes in extreme weather events, such as heat and cold waves (*Kotwicki* and *Al Sulaimani,* 2009; *Almazroui et al.,* 2012b). For example, the climatic extreme event in 2010 was considered as the warmest year of the observational period over Saudi Arabia (*Almazroui et al.,* 2012a). On June 2010, the temperature over Saudi Arabia was recorded at 52 °C. Based on the observed daily temperature datasets from 19 stations for the thirty-year period from 1979 to 2008, *Athar* (2014) studied the extreme climate over Saudi Arabia using climatic indices. According to his findings, the frequency of the extreme cold temperatures is less than the frequency of the extremely warm temperatures on seasonal and annual basis. In addition, the daily extreme temperature is warmer during the summer season. Moreover, the southwest coastal region has displayed more warming than the inland region. Also, during the thirty-year-long period, the statistically significant increase of the daily regional temperature is 0.21 °C per decade. Lastly, warming in general is noticed by him over Saudi Arabia, especially in maximum temperatures. The results of *Athar* (2014) agreed with the results of *AlSarmi* and *Washington* (2014), who studied the changes in temperature extremes over the Arabian Peninsula based on daily data over 23 stations covering six countries (Saudi Arabia, Oman, Bahrain, Qatar, Kuwait, and UAE) at different time periods. *AlSarmi* and *Washington* (2014) found a significant increase in very warm nights during the period from 1986 to 2008. Moreover, they noticed in general, that extreme temperatures over the northern Arabian Peninsula in the daytime are high, while for the nighttime, extreme temperatures are observed over the southern region, especially during the last period of the study. From the spring to autumn, strong warming above 5 days per decade is found (*Islam et al.,* 2015). *Almazroui* (2020) studied the extremes in the temperature over Saudi Arabia for the period 1978–2019 and found an increase in the average temperature extremes over the second period (2000–2019) as compared to the first period (1980–1999). The results show a considerable increase in the number of warm days/nights in the second period compared to the first period. The results also exhibit a considerable decrease in cold days/nights. Moreover, in the summer season, an increase in warm days/nights is observed, while in the winter season, a decrease in the number of cold days/nights is found.

6. Circulation weather types and their influence on the surface air temperature

6.1. Overview

The atmospheric circulation such as low and high pressure plays an important role in determining weather and climate. Centers of high or low pressure over Asia generally immigrate from east to west, and these centers change radically from wintertime to summertime. The various systems that control pressure over Saudi Arabia during different seasons are the Siberian high over central Asia, the Indian low and monsoon Asiatic (*Hastenrath,* 1985), and the Mediterranean secondary low pressure (*Kendrew,* 2012). In wintertime, a thermal high pressure called Siberian high pressure is developed over Mongolia, which controls the eastern and southern climates of Asia. This thermal high pressure is shallow, cold, and dry which extends to southwest Asia through southern and eastern regions of Asia. The Siberian high pressure exists from November to March, and it reaches the maximum value in February over Asia. February marks the peak of the Siberian high's overriding of the winter circulation over Asia, while a similar pattern, depicted on the January map, exists from November to March. February indicates the maximum of the Siberian high's control of the circulation in the wintertime over Asia, though the same distribution pattern has been observed in January, and from November to March. This is related to the advection of dry, cool, and subsiding polar continental air mass. Moreover, in April, the Siberian high pressure weakens and shifts to central Asia, then it disperses in May, when intense thermal low dominates over the tip of the Arabian Peninsula (*Davydova et al.,* 1966).

From March to May (spring season) and from September to November, the Saudi Arabian (autumn season) tropical disturbances (may intensify into tropical storms, but it is rare to grow into tropical cyclones) are invaded in the Arabian Peninsula. Tropical cyclones occur in the period from October to December, but their impact is limited to the southern part of the Arabian Peninsula (*Taha et al.,* 1981). Also, very dry and hot continental tropical air from the Sahara arrives in the area during early autumn and late spring.

From June to August (summer season), the Asian monsoon (Indian monsoon) low pressure dominates over the Arabian Peninsula (*Hastenrath*, 1985). Moreover, the Azore's high pressure (subtropical high pressure) affects the western rim of the Arabian Peninsula. Very hot and dry air masses arrive irregularly in the region from northern India after the tropical maritime air loses its moisture. Moreover, the neighboring water surface of the Gulf Sea, the Gulf of Oman, and the Arabian Sea contributed as the sources of moisture (*Taha et al.,* 1981). Additionally, in summer, the intertropical front forms from the meeting of converging air masses over the Arabian Peninsula region. Moreover, the water surface near the Arabian Sea and the Gulf of Oman works as a source of moisture and heat (*Taha et al.,* 1981). The main characteristics to be considered in the climate of Saudi Arabia are the topographic and the interior regions, especially in the western region along the Red Sea (*Al-Jerash* 1985; *Ahmed* 1997; *Subyani et al.,* 2010; *Almazroui et al.,* 2012a).

6.2. Synoptic circulation in the winter season

In the winter season, the synoptic circulation systems that affect SAT of Saudi Arabia are the Siberian high pressure extended from the east, subtropical high pressure extended from the west, Sudan low pressure extended from the south, and Mediterranean depressions and/or Icelandic low extended from the north (*Fig. 3*). These synoptic circulation systems generate weather activity over the Saudi Arabian region, which is summarized below.

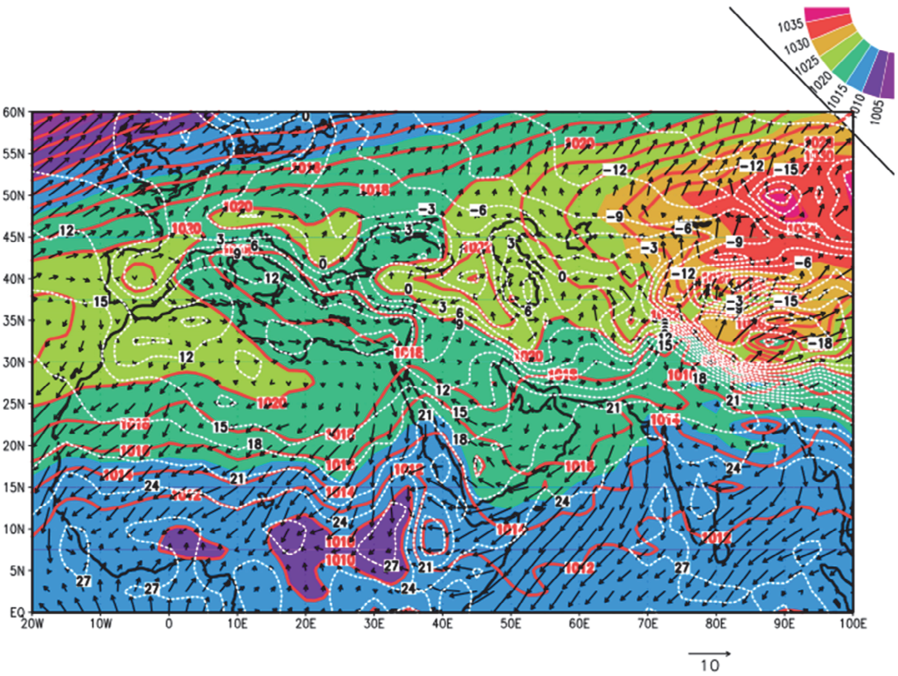

Fig. 3. The distribution pattern of sea level pressure (solid red curve), surface air temperature (small dash curve), and vector wind in the winter season.

A) The Mediterranean depressions on the surface are in relationship with upper troughs coming from the west to east, the active subtropical jet, and the polar jet making precipitation during their transit over Saudi Arabia region. Their potential of producing weather activity decreases generally from north to south over the area except for the mountainous areas, where the uplift acts as an exterior factor. Consequently, the distribution of winter weather activity shows maximum movement in the northern part of the main plateau with a gradual decrease in the lowlands in the eastern and western sides. The trough emanates from the Icelandic low extends southward influencing the weather in Saudi Arabia (*Hasanean et al.,* 2015). A positive relationship exists between the Icelandic low and SAT over the northern parts of Saudi Arabia (*Fig. 4*, *Hasanean et al.,* 2015; *Attada et al.,* 2019). Therefore, the SAT decreases (cooling) during the deepening of the Icelandic low (*Fig. 5a*), while it increases (warming) during the weakening of the Icelandic low (*Fig. 5b*).

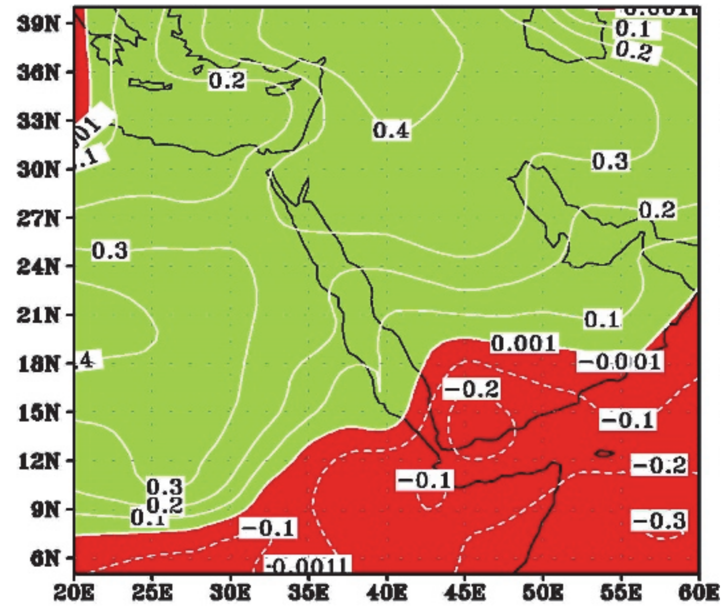

Fig. 4. Horizontal distribution of the correlation coefficient between the SAT and the Icelandic low pressure (*Hasanean et al.,* 2015).

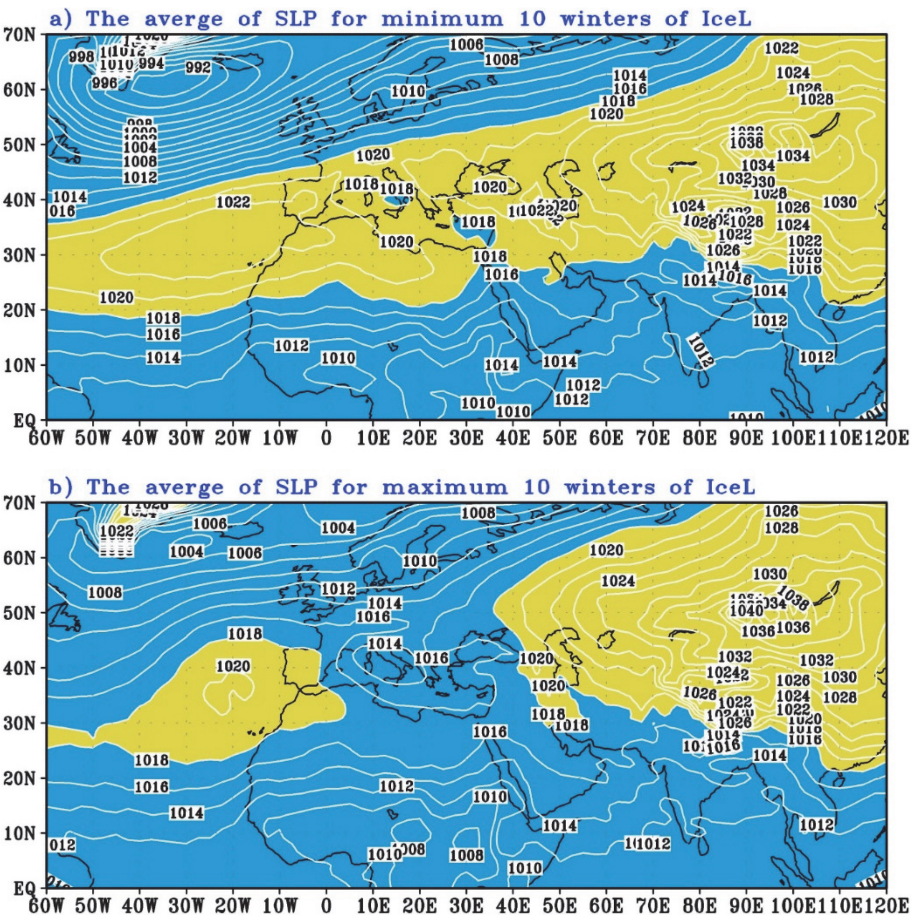

Fig. 5. Composite sea level pressure pattern for the ten winters, when the Icelandic low was (a) deepening and (b) weakening (*Hasanean et al.* 2015).

B) The major pressure system influencing the climate of Saudi Arabia in winter is the Siberian high pressure over Asia, that tends to merge with centers of high pressure over the Arabian Peninsula (Saudi Arabian high) and Sahara Desert (Saharan high). The Siberian high pressure in winter centered over northern Mongolia extends southward to cover Saudi Arabia and the Arabian Gulf carrying cold air to these regions. The Siberian high-pressure influences the climate of mid-high latitudes (*Guo,* 1996; *Zhu et al.,* 1997; *Gong* and *Wang* 1999; *Miyazaki et al.,* 1999; *Yin,* 1999; *Hasanean et al.,* 2013*,* 2015). A positive relationship between the Siberian high pressure and SAT is found over the northern region of Saudi Arabia extending to the central regions (*Fig. 6*, *Hasanean et al.,* 2013, 2015; *Attada et al.,* 2019). Therefore, the SAT warms in the northern and central regions of Saudi Arabia during the intensification of the Siberian high pressure in the winter season.

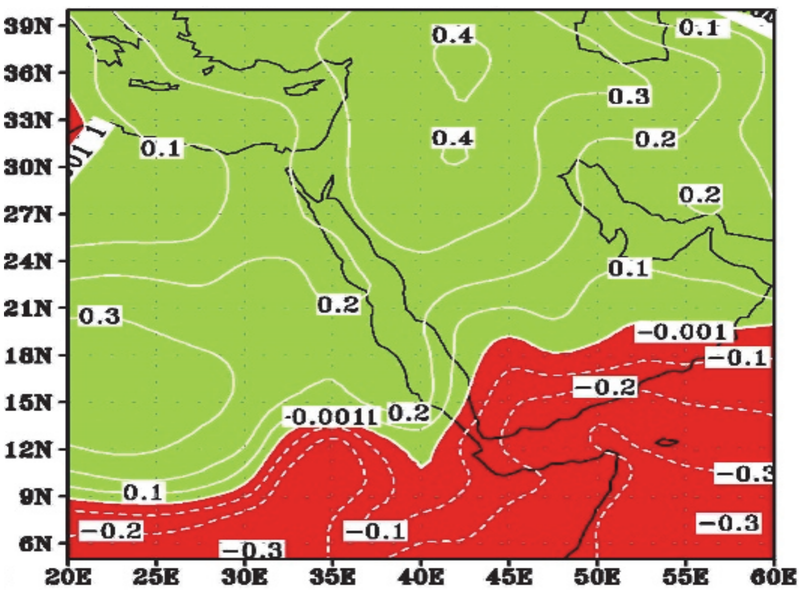

Fig. 6. Horizontal distribution of the correlation coefficient between the SAT and the Siberian high pressure (*Hasanean et al.,* 2015).

Fig. 7a reveals the composite 10 years of sea level pressure difference between the maximum and minimum of the Siberian high pressure. Cooling of SAT over Saudi Arabia, Egypt, the northeast of the Mediterranean, and Sudan (*Fig. 7a*) is found during the minimum of the Siberian high pressure. This cooling of SAT is between 0.5 ^{o}C in the southern region of Saudi Arabia and 2.0 ^{o}C over the northern region of Saudi Arabia and the Turkish area. This is because the Siberian high dominates over the Saudi Arabia region providing very cold and dry air during the deepening of the Siberian high pressure. Two sources of relatively warm moist air, one from southern Europe and the other from the southern and southeast parts of Saudi Arabia are invaded during the years of weakening Siberian high pressure (*Fig. 7b*). *Fig. 7b* shows the composites of 10 winters of the sea level pressure when the Siberian high was strong. In this case, the Siberian high is separated from the subtropical high pressure, and the pressure over Saudi Arabia and the southern Mediterranean regions becomes weak. Therefore, the distribution pattern of the sea level pressure, in this case, leads to interlinkage among two different air masses, first with the cold moist air mass coming from the Mediterranean depression, which is traveling from west to east, and second with the warm moist air coming from the northward oscillation of the Sudan low. The interlinkage between these pressure systems leads to an increase of the SAT over Saudi Arabia, the east of Africa, southeast Europe, and the east Mediterranean.

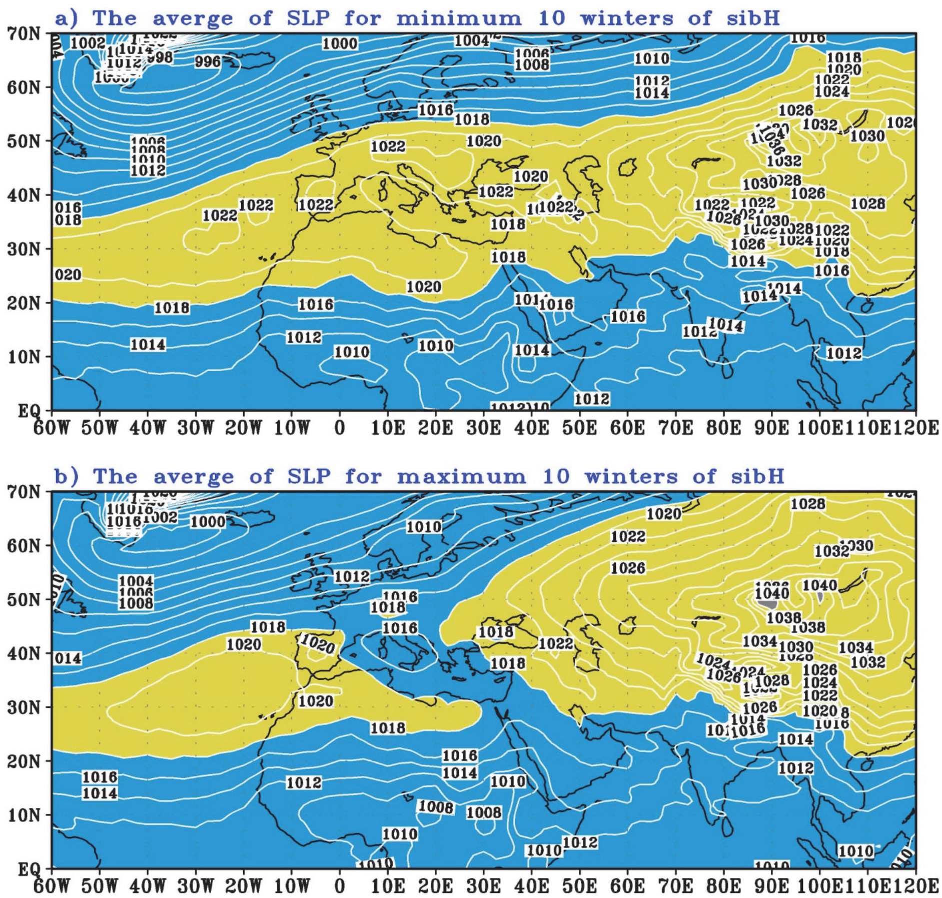

Fig. 7. Composite sea level pressure pattern for the ten winters, when the Siberian high was (a) weakening and (b) strongest (*Hasanean et al.* 2015).

C) The dominant subtropical high pressure (Azores High) is situated around the latitudes of 30° N in the Northern Hemisphere and forms a broad continuous ridge in the mid-latitudes and the subtropical region. The movement and oscillation of the surface subtropical high are associated with the movement and oscillation of the Siberian high (*Hasanean et al.,* 2015). *Barry and Chorley* (1992) explained that the movement of the subtropical high toward the equator through the winter is due to the increasing temperature differences between the tropics and the poles. Saudi Arabia is influenced by the extension of the subtropical high pressure. *Hasanean et al.* (2015) investigated the relationship between the subtropical high and SAT and found, that in the greatest parts of Saudi Arabia with the exception of the southwest area, an inverse relationship between the subtropical high-pressure and SAT exists (*Fig. 8*). Therefore, intensifying (weakness) in the subtropical high-pressure leads to a decrease (increase) in the SAT. The SAT over Saudi Arabia is warming during the weakness of the subtropical high pressure, where the warm air mass comes from the southern parts of Europe (relatively warm) and the southern/southeastern parts of Saudi Arabia. During the subtropical high pressure intensity, SAT is cooling due to very cold and dry air masses coming from Siberian high pressure (*Hasanean et al.,* 2015).

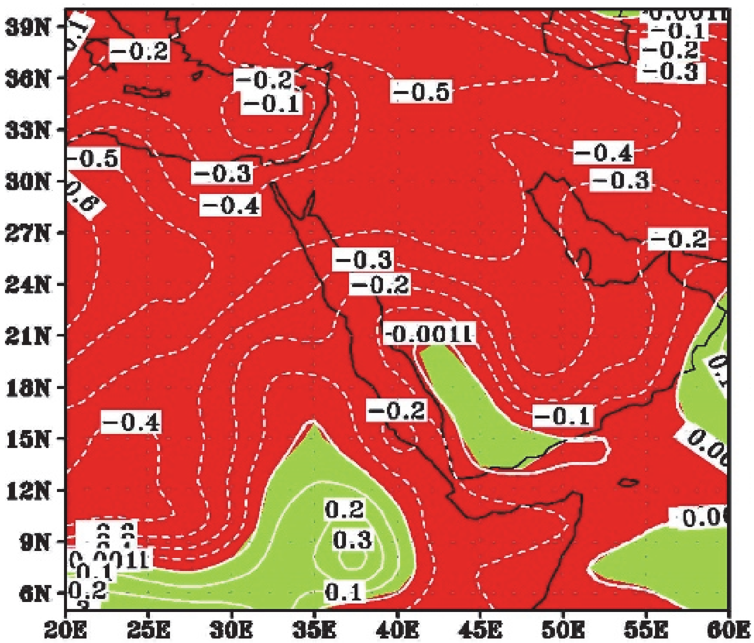

Fig. 8. Horizontal distribution of the correlation coefficient between the SAT and the subtropical high pressure (*Hasanean et al.,* 2015).

D) *Vorhees et al.* (2006) and *Hasanean et al.* (2013) noticed that in winter, the Saudi Arabian high pressure plays an important role in the climate of southwest Asia. *Fig. 9* reveals the typical circulation distribution patterns over the Arabian Peninsula and northeast Africa in winter. The Saudi Arabian high is on the northern, Mediterranean low pressure systems are on the northwest parts of the Arabian Peninsula. Moreover, when the Saudi Arabian high pressure is prevailing, the air is more stable and relatively warmer within the area. At the same time, the Siberian high pressure prevents the Mediterranean depression, and consequently, the northwest wind (cold air) comes into the area.

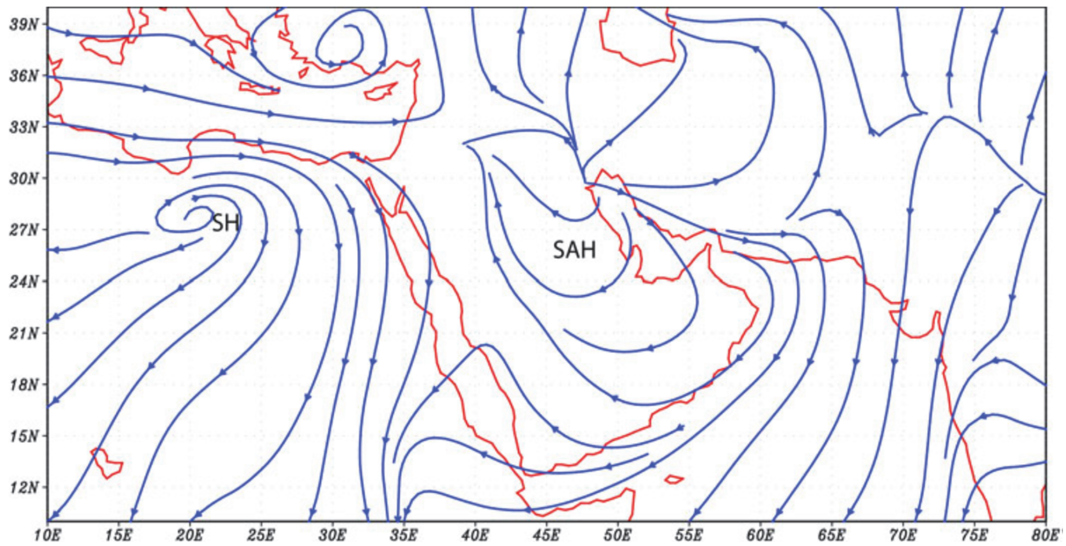

Fig. 9. Long-term mean surface streamlines associated with the Saudi Arabian high (SAH) and the North African high (Sahara high, SH; (*Hasanean et al.,* 2015)).

E) The Sudan low is a dynamic low pressure that carries humid and warm air to Saudi Arabia and the south of the Mediterranean Sea in the cold and rainy seasons (*Rasuly et al.,* 2012). The Red Sea trough (RST) is counted as an expansion of the Sudan low (*El-Fandy,* 1948). So, one can say that the southward and/or northward oscillations of the Red Sea trough arises from the southward and/or northward oscillations of the Sudan low. Usually, the movements of the Sudan low can be classified into two different kinds of oscillations. The first is the movement of its center from near to the Abyssinian Plateau and its return, twice over the year. The second comprises a series of quite small oscillations superimposed on the annual track. These small oscillations are most evident in the two transitional seasons (*El Fandy,* 1940). A strong negative relationship between the Sudan low and SAT over the northern and central areas of Saudi Arabia is found (*Fig. 10*, *Hasanean et al.,* 2015). Therefore, the SAT warms over all regions of Saudi Arabia except for the southern region during deepening (decrease in mean sea level) of the Sudan low, and the SAT colds during the weakening of the Sudan low (increase in mean sea level).

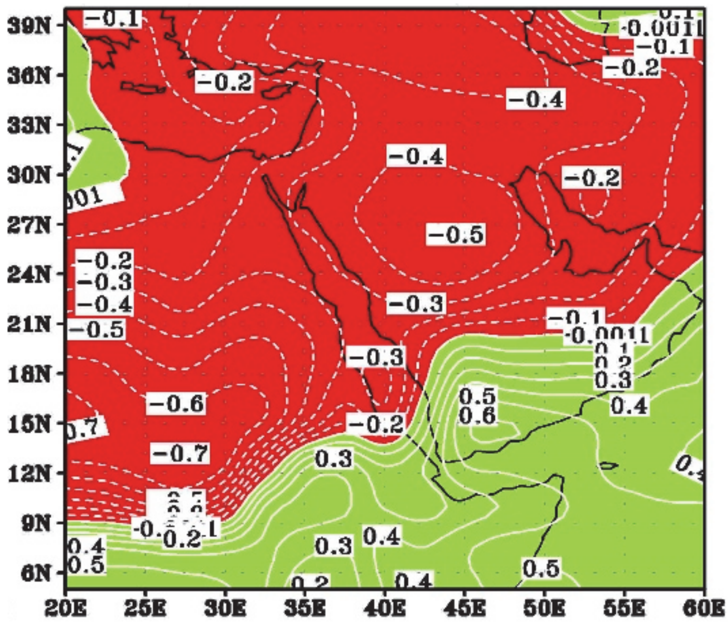

Fig. 10. Horizontal distribution of the correlation coefficient between the SAT and the Sudan low pressure (*Hasanean et al.,* 2015).

According to *Hasanean et al.* (2015), two main distribution patterns of pressure affect the SAT of Saudi Arabia. The first pattern happens when the subtropical high pressure is strengthening, Siberian high is weakening, Icelandic low is deepening, and Sudan low is weakening. In this situation, the subtropical high pressure merges with the Siberian high pressure to prevent the interaction between the extratropical and midlatitude systems that leads to cooling SAT. The second situation occurs when the subtropical high pressure is weakening, Siberian high pressure is strengthening, Icelandic low is weakening, and Sudan low is deepening. This pattern causes interaction between two different air masses, the first is a cold moist air mass that is related to the traveling Mediterranean depression from west to east and the second is a warm moist air mass related to the northward oscillation of the Sudan low pressure and its inverted V-shape trough.

There are exchanges between air masses arising from high and low pressure systems that influence the SAT over Saudi Arabia. For an instant, there is an exchange of air mass between the subtropical high pressure and Icelandic low to build up the North Atlantic oscillation, which is linked to SAT variability (*Rogers* and *van Loon* 1979; *Rogers,* 1984). When the North Atlantic oscillation index becomes negative (subtropical high pressure and Icelandic low are weak), the relatively warm moist air moves to lower latitudes. On the other hand, during positive North Atlantic oscillation index, the stronger clockwise current around the subtropical high center is remarkable, and the temperature over the Middle East is cooling (*Hurrell et al.,* 2003). In winter, the subtropical high-pressure retreats southwestward, and the Red Sea trough oscillates northward over the eastern Mediterranean area (*Alpert et al.,* 2004), and the Siberian high pressure moves eastward to bring the mild temperature to the Arabian Peninsula. On the other hand, during the weakening of the Siberian high pressure, few depressions moves to the Mediterranean (*Makrogiannis et al.,* 1991; *Sahsamanoglou* and *Makrogiannis* 1992; *Wilby* 1993), which affects Saudi Arabia, especially its northern region.

6.3. Synoptic circulation in the spring season

The weather of Saudi Arabia during the spring season is affected by the Sudan monsoon low, which is entering from the southeast (*Fig. 11*). *Attada et al.,* (2019) investigated the surface air temperature variability over the Arabian Peninsula and its links to circulation patterns. They found a negative (positive) relationship between the SAT and the subtropical high pressure (Siberian high pressure) over the Arabian Peninsula during the spring season (March, April, and May). Therefore, the SAT warms during the strengthening of the subtropical high pressure and the weakening of the Siberian high pressure. They suggested that the variability of temperature in the spring season is related to the strongness/ weakness of the Siberian high pressure. Therefore, when the Siberian high pressure is strong and extends to the Saudi Arabia region, the SAT becomes cold, and vice versa, when the Siberian high pressure is weak. The Arabian Peninsula is influenced by northeasterly winds blowing from the Indian region, proposing that the spring temperature over the Arabian Peninsula is related to the Mediterranean depression and Siberian high pressure (*Attada et al.,* 2019). Moreover, at this time, the SAT is influenced by the weak westerly windsof the upper trough in the mid-troposphere because of the change taking place over Asia. These changes take place in a relatively short time due to the thermal equator that moves northward. In addition, in the spring season, strong contrast in temperature between sea and land and between valleys and mountains occurs. There exists a contrast in temperature, where cool moist air (polar maritime and polar continental air) comes from the eastern Mediterranean, and warm air temperature exists over the desert (tropical continental air). The inverse relationship between sea level pressure and SAT over Saudi Arabia is found (*Attada et al.,* 2019).

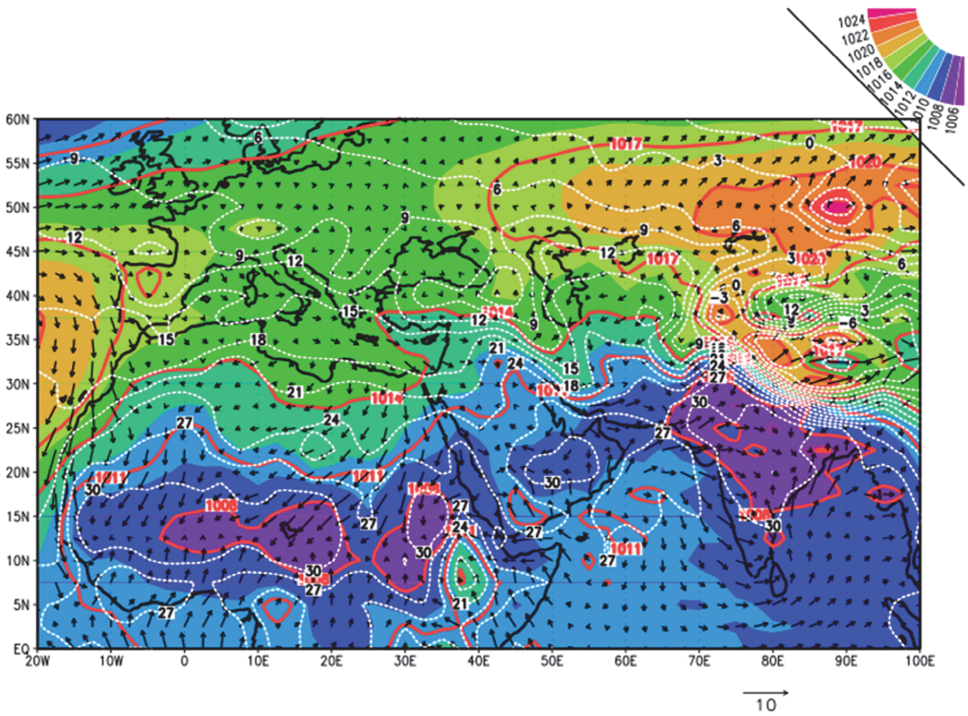

Fig. 11. The distribution pattern of the sea level pressure (solid red curve), surface air temperature (small dash curve), and wind vector in the spring season.

6.4. Synoptic circulation in the summer season

The distribution patterns of SAT become uniform over the Arabian Peninsula with intense temperatures (above 36 ºC) which are found in the eastern region, and minimum temperatures (30 ºC) over the northern part and the mountains of the southern region of the Arabian Peninsula in the summer season (*Fig. 12*). These results agree with the study of *Attada et al.* (2019). *Izumo et al.* (2008) and *Yao* and *Hoteit* (2015) illustrating that the SATs over the mountain of the southern region of the Arabian Peninsula decrease due to strong cross-equatorial flow along the Somalian coast, which cools the sea surface temperature of the western Arabian sea. The highest SATs in the summer season over the desert regions arise from the descent motion, which causes adiabatic warming (*Khan* and *Alghafari,* 2018; *Babu et al.,* 2018; *Attada et al.,* 2019). *Rodwell* and *Hoskins* (1996) and *Rodwell and Hoskins* (2001) found, that the descent motion is due to the monsoon-desert mechanism and stronger summer solar isolation. *El Kenawy et al.* (2014) and *El Kenawy* and *McCabe* (2016) illustrated, that the high temperature creates a thermal low that increases the cyclonic activities over the Arabian Peninsula. A strong and positive relationship is found between the SAT over the Arabian Peninsula and the mean sea level pressure over the regions of the Indian subcontinent and East Asia, but a negative relationship is found with the Saharan heat low and the equatorial Atlantic Ocean (*Attada et al.,* 2019; *Babu et al.,* 2018). Also, *Attada et al.* (2019) found a cyclonic circulation over the Sahara in North Africa and the western Mediterranean regions that intensifies the Saharan thermal low and influences the SAT of the Arabian Peninsula. The convergence of air arising from the easterly wind from the equatorial Indian ocean and the westerly wind from Africa moves toward the Arabian Peninsula. The Indian summer monsoon and the Sudan low are the major synoptic circulations that influence Saudi Arabia from the south (*Almazroui et al.,* 2012a).

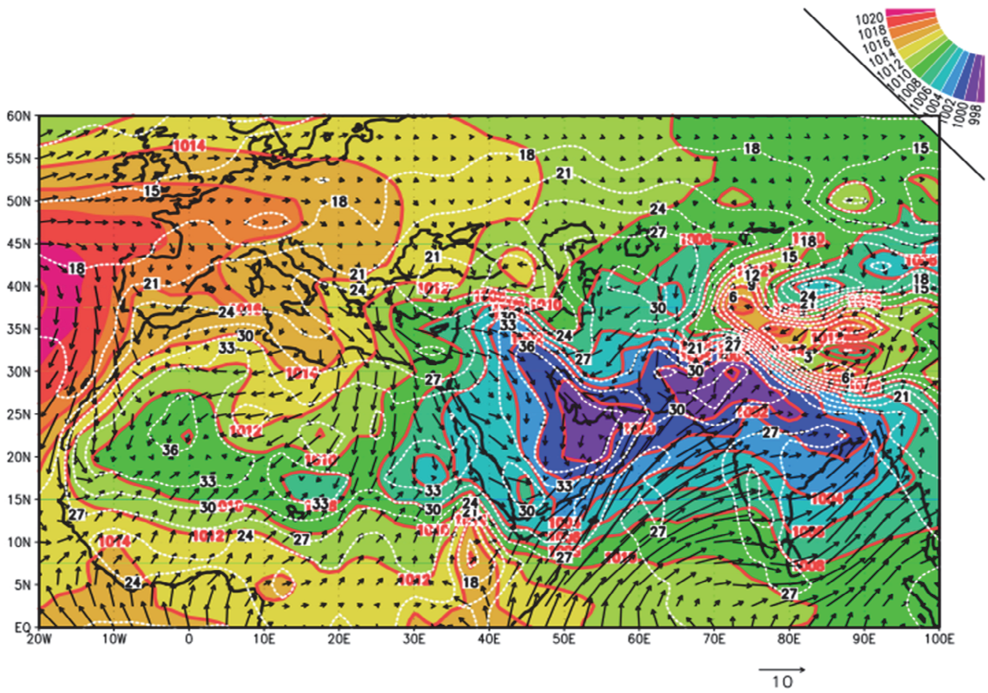

Fig. 12. The distribution pattern of the sea level pressure (solid red curve), surface air temperature (small dash curve), and wind vector in the summer season.

The orography and the distances from main bodies of water in the western parts of Saudi Arabia along the Red Sea coast have effects on the climatic distribution pattern of temperatures (*Al-Jerash,* 1985; *Ahmed,* 1997; *Subyani et al.,* 2010; *Attada et al.,* 2019). The main structures to be considered are the difference between the shore and inner areas; and the difference between the two shore zones and the windward and leeward sides of the mountains ranging from the south to north. The thermal low of the Indian monsoon is centered over northwestern India, Pakistan, and Baluchistan, which expands to the Arabian Peninsula and creates a strong heat on the surface. Another thermal low develops along the plain of southern Iraq that leads to the “shamal” winds (northwest and hot dusty winds), which blow southeastward across Kuwait and down into the Gulf (*Aurelius,* 2008). Above sea level from one to two kilometers of the Arabian Sea, the wind direction is shifted from southwest to northwest with an increase in temperature with elevation (inversion), while northwesterly wind adverts tropical continental air mass from the "empty quarter". Upwelling is arising from the southwesterly wind when blowing over cold coastal water. Therefore, the outcome of the cold sea is to cool the maritime air mass of the lowest layers.

Usually, the shamal winds ease the SAT in summer. In some cases, the shamal winds arising from a dry cold front in the Arabian Peninsula decrease the maximum temperature by 5 ºC (*Aurelius,* 2008). In mid-July, the pressure gradient becomes weak in the area leading to a period of light northwesterly winds, and the shamal winds become weak. Usually, over Iraq, a thermal low develops that leads to a weak pressure gradient over the eastern region of Saudi Arabia and near Kuwait (*Preusser et al.,* 2002). *Fig. 12* illustrates the distribution pattern of sea level pressure and the wind vector in the summer season. Southeast Asia is dominated by the Indian monsoon. The Indian monsoon during a strong period (mid-August) extends to the Mediterranean Sea that breaks the frontal system from invading the area and pushing the subtropical high pressure east of Saudi Arabia. Southern Arabia is affected by the western margin of monsoon circulation, which controls the wind field and the amount of precipitation acting in terrestrial environments (*Preusser et al.,* 2002). At present, atmospheric circulation in summer is dominated by a series of low pressure cells that are located along the intertropical convergence zone (ITCZ) and across southern Arabia.

6.5. Synoptic circulation in the autumn season

In Saudi Arabia, the SAT, in general, is between 20 °C to 25 °C. The highest values of SAT are observed over the eastern and southeastern areas of Saudi Arabia, while the SAT is below 25 °C in the western and northwestern areas (*Fig. 13*). These results agree with the study of *Attada et al.* (2019). The mean SAT is about 29 °C in the autumn season in Saudi Arabia. During the autumn season, the weather of Saudi Arabia is influenced by the Sudan monsoon low, such as in the spring season, which is entering from the southeast (*Fig. 13*). Also, Saudi Arabia is influenced by the early Mediterranean depressions, which cause activity in weather when the southerly hot air mass meets the cold air mass over the northern region of Saudi Arabia. At the end of November, the troughs moving to eastward in the upper troposphere and the yearly cycle renews (*Ghazanfar* and *Fisher,* 1998). Strong negative correlations between the SAT and the mean sea level pressure in autumn over the Sahara and North Africa are observed (*Attada et al.,* 2019). Due to the intensification of the Sahara heat low and its movement towards the south of the Arabian Peninsula, surface air temperature increases over Saudi Arabia.

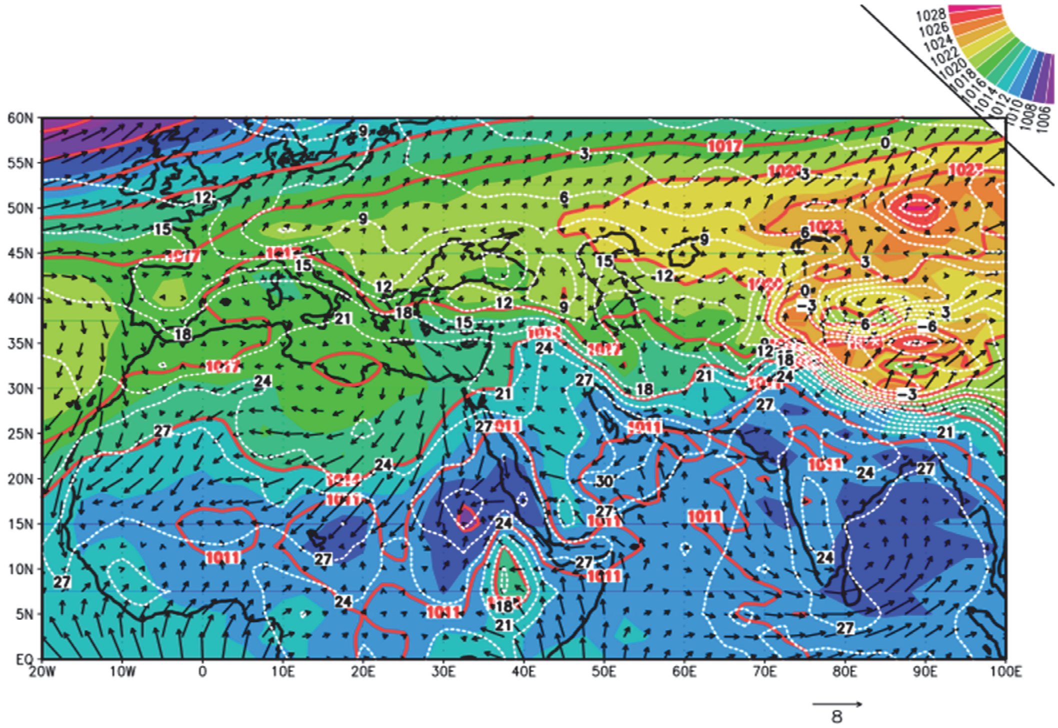

Fig. 13. The distribution pattern of the sea level pressure (solid red curve), surface air temperature (small dash curve), and wind vector in the autumn season.

7. Conclusions

The main findings of this review article can be summarized as follows:
For the past climate, from about 650 ka BP to the present, the SAT over Saudi Arabia during the earlier period is higher than in the present period due to atmospheric greenhouse gases (*Jansen et al.,* 2007). The climate over the world fluctuates/changes from cold to while it was warm from time to time. By the date 150,000 BCE, the climate was cold, warm in 140,000 BCE, similar to the present climate in 130,000 BCE, cold in 120,000 BCE, the gradual warming continued in 9500 BCE, and the cold periods prevailed for the next thousand years (*Edmiston,* 2007). The climate in the six periods (9,000–8,000, 6,000–5,000, 4,200–3,800, 3,500–500, 1,200–1,000, and 600–150 BP) are featured by polar cooling, tropical aridity, and main atmospheric circulation changes (*Mayewski et al.,* 1981). During the 8,000s BP, a 200-year-long cooling period occurred (*Edmiston,* 2007). Due to climate change, during four successive ice ages, hot periods in the Pleistocene were observed over Saudi Arabia (*Kotwickiet al.,* 2007).

For the present situation, the climates over Saudi Arabia vary from place to place due to the impact of climatic controls such as the difference between landmass and water-body, air masses, mountains barriers, elevations above mean sea level, atmospheric circulations, and ocean currents. Moreover, Saudi Arabia has occupied a vast area (about 80% of the Arabian Peninsula); therefore, the temperature is different in space and time. The climate of Saudi Arabia is a desert climate (warming in the daytime and sudden cooling in nighttime) with the exception of the mountainous region in the southwest. Saudi Arabia is the warmest region in the summer season (above 50 °C) around the globe except for the coastal region. Over the north of the Tropics of Cancer and the inland of Saudi Arabia, high temperatures are observed. On the other hand, moderate SATs are found in the southwest highlands and northwest regions. The features of the climate of the Saudi Arabia are arid to semi-arid (*Köppen* and *Geiger,* 1928; *Walter* and *Lieth,* 1967; *Troll* and *Paffen,* 1980; *Muller,* 1982; *Moore,* 1986; *Almazroui et al.,* 2012a, 2012b). In addition, the seasonal temperatures are high in the central and northern regions compared to the southern region. Moreover, the diurnal temperature is characterized as high during the day and has an abrupt drop at night.

Four different types of air masses affect the climate elements of Saudi Arabia, as follows.

During wintertime, the polar continental air mass affects Saudi Arabia that comes from the Siberian high, which is dominant in central Asia and extends to the Arabian Peninsula. In addition, during winter, polar maritime air masses coming from the mid-latitude depression from the west influence the climate of Saudi Arabia. In spring and early summer, the tropical continental air mass influences the climate of Saudi Arabia. Also, during summer and autumn, the tropical continental air mass prevails over Saudi Arabia through the Indian monsoon. Moreover, during summer, the tropical maritime air mass comes from the north of the Indian Ocean and the Arabian Sea, which affects mainly the southwestern region of Saudi Arabia bringing hot and humid air.

SATs over Saudi Arabia are different from season to season due to different air masses that invade the region. During the winter season, SAT over the southeastern region is high, and it is higher than in the southwestern region due to the local topographical effect, it is moderate over western and central regions, and low over the northern region due to Mediterranean depression. During spring in the northern region, the SAT increases faster than over other regions of Saudi Arabia except for the eastern region. During the summer season, the eastern region of Saudi Arabia is warmer than the southern region. Unusually high SAT over desert areas exists due to the strong descent motion. The SAT in the summer season is the warmest due to the dominant Indian monsoon low over Saudi Arabia. The SAT during the autumn season is moderate (around 29 °C) over Saudi Arabia, while in the western and northwestern regions are lower than the eastern region of Saudi Arabia.

Mean annual SATs over Saudi Arabia are between 24 °C–30 °C. The highest mean annual values of the SAT are observed over the Al-Rub Al-Khali and southwest mainly along the Red Sea coast. Whereas, the lowest SATs (around 21 °C) are observed in the northern area. Low annual mean minimum of SAT

(6 °C–15 °C) is found over the northwestern and southwestern areas of Saudi Arabia. The SATs in the southeastern region (mainly over Al-Rub Al-Khali) are relatively high. The annual mean maximum SATs (between 27 °C and 33 °C) are found over the most regions of Saudi Arabia. The highest mean maximum SAT (33–36 °C) is observed over the central parts of the country and in the southwest region, while a slightly lower mean maximum SAT is found along the Red Sea coast.

Over Saudi Arabia, the warmest year is 1999 and the coldest year is 1992, according to the second report of the UNFCCC. The summer 2010 is the warmest season with an outstanding temperature (52.0 °C) observed in the city of Jeddah. During the coldest year, in winter and early spring, central and northern regions of Saudi Arabia have extreme cooling that associates with the invasion of the Siberian high, while during the warmest year, in summer and early autumn, the central and most of the eastern coasts and northeastern regions of Saudi Arabia have extreme warming, that associates with an extension of the Indian monsoon. Based on daily observations, the extreme SAT is warmer during the summer season (*Athar,* 2014; *AlSarmi* and *Washington,* 2014). *AlSarmi* and *Washington* (2014) noticed, that the northern region of the Arabian Peninsula has high SAT in the daytime, while the southern region has high SAT in the nighttime. In addition, the frequency of the extreme warm SAT is greater than the extreme cold SAT based on seasonal and annual observations. Moreover, the southwest coastal area has shown more warming than the inland area. Over most stations of Saudi Arabia, strong warming above 5 days/decade is found during the spring to autumn seasons (*Islam et al.,* 2015). In addition, it is observed during these seasons, that the number of warm daytimes increases rapidly compared to the number of warm nighttimes during spring, summer, and autumn seasons over most stations of Saudi Arabia.

The atmospheric circulations (low and high pressure) play a vital role with regard to weather and climate. In general, it can be concluded that the Siberian high pressure is controlling the SAT of Saudi Arabia in the winter season, and the Indian monsoon low is controlling the SAT in the summer season (*Davydova et al.,* 1966; *Vorhees* 2006; *Hasanean et al.,* 2015; *Babu et al.,* 2018). In addition, the synoptic circulation patterns in spring and autumn are complicated, when centers of high and low dominate the regions of Saudi Arabia. During the spring and autumn seasons, the extended Mediterranean low pressure influences the northern region and the Sudan monsoon low/ Red Sea trough influence the southern region of Saudi Arabia, while subtropical high pressure impacts the western region, and the Siberian high pressure impacts the eastern region of Saudi Arabia.

During the spring season (March, April, and May),the subtropical high pressure from the west and the Siberian high pressure from the east effect the SAT of Saudi Arabia. The subtropical high pressure and the Siberian high pressure affect each other. When Siberian high pressure is strong and extends to the Saudi Arabian region, the subtropical high pressure is weak and the SAT is cold and vice versa; when the Siberian high pressure is weak, the subtropical high pressure is strong, and the SAT is warm. The SAT of Saudi Arabia is influenced by the Mediterranean depression from the north and may extend to the central region, which brings cold air, and the Sudan monsoon low from the south may extend to the north that brings warm and moist air (*Attada et al.,* 2019). The circulation pattern in the autumn season is similar to the circulation pattern in the spring season.

The main features to be considered in the synoptic circulation patterns of Saudi Arabia in the different seasons are as follows.

During the winter season, the synoptic circulation features that influenced the SAT of Saudi Arabia are: the trough emanating from the Icelandic low (cold moist air mass), which extends southward influencing the weather in Saudi Arabia (*Hasanean et al.,* 2015; *Attada et al.,* 2019). The SAT decreases (cooling) during the deepening of the Icelandic low, while it increases (warming) during the weakening of the Icelandic low. In addition, the Siberian high pressure is dominant over Asia (cold air mass), and it tends to merge with high pressure centers over the Arabian Peninsula (Saudi Arabian or Saharan high pressure) (*Guo,* 1996; *Gong* and *Wang,* 1999; *Miyazaki et al.,* 1999; *Yin,* 1999; *Hasanean et al.,* 2013*,* 2015). The SAT warms in the northern and central regions of Saudi Arabia during the intensification of the Siberian high pressure in the winter season (*Hasanean et al.,* 2013*,* 2015; *Attada et al.,* 2019).

In the winter season, the SAT is cooling when the Siberian high pressure is deepening and dominating over Saudi Arabia that prevents the Mediterranean depression, while the SAT is relatively warm when the Siberian high pressure is weakening, where the relatively warm moist air is blowing from southern Europe and from the southern and southeastern parts of Saudi Arabia. The SAT of Saudi Arabia is influenced by the extension of the subtropical high pressure, which is related to the movement of the Siberian high pressure to the east and/or to the west (*Barry,* 1992; *Hasanean et al.,* 2015). The SAT is relatively warming when the subtropical highpressure is weakening, and the SAT is cooling when the subtropical high-pressure is deepening. The Saudi Arabian high pressure, as a relatively small feature, plays an important role in the SAT in the winter season (*Vorhees*, 2006; *Hasanean et al.,* 2013). When the Saudi Arabian high pressure dominates over the region, the air is more stable, and the SAT is relatively warm across the region. Moreover, the Sudan low and the Red Sea trough are influencing the SAT of Saudi Arabia in the winter season (*Rasuly et al.,* 2012), carrying humid air to the region. When the Sudan low is weakening, the SAT is cooling, and when Sudan low is deepening, the SAT is relatively warming (*Hasanean et al.,* 2015; *El-Fandy,* 1940, 1948; *Hasanean et al.,* 2013). Two circulation patterns dominate the SAT of Saudi Arabia in the winter season, the first pattern is when the subtropical high pressure merges with the Siberian high pressure to prevent the interaction between extratropical and mid-latitude systems that leads to cooling of the SAT (*Hasanean et al.,* 2015). The second pattern is when the subtropical high pressure is weakening, the Siberian high pressure is strengthening, Icelandic low is weakening, and Sudan low is deepening (*Hasanean et al.,* 2015) that allow two different air masses to invade Saudi Arabia (cold moist air mass from the Mediterranean depression from west, and warm moist air mass from the Sudan low pressure from south), (*Hasanean et al.,* 2015).

During the spring season, when the Siberian high pressure is deepening, the SAT is coolingm while when the subtropical is deepening, the Siberian high pressure is weakening and the SAT is warming (*Attada et al.,* 2019). In addition, the Mediterranean depression can influence the SAT when extending to the northern region of Saudi Arabia and cooling the region. From the southern region, the Sudan low is extending to the northern region and/or Asian monsoon low is extending from the east thereby warming Saudi Arabia.

During the summer season, the Indian summer monsoon and the Sudan low are the major synoptic circulations influencing the SAT of Saudi Arabia (*Almazroui et al.,* 2012a; *Babu et al.,* 2018; *Attada et al.,* 2019). Another thermal low develops along the plain of southern Iraq leading to the "shamal" winds over the eastern parts of Saudi Arabia (*Aurelius,* 2008). The Indian monsoon may extend to the Mediterranean Sea, which cuts the frontal system and pushes the subtropical high pressure to the east of Saudi Arabia. When the subtropical high pressure is strengthening and extending eastward, it influences the SAT in the western region of Saudi Arabia relatively cooling the region. In addition, when the Saharan thermal low is deepening over North Africa, it influences the SAT of Saudi Arabia.

During the autumn season, the Sudan monsoon low coming from the southeast influences the SAT of Saudi Arabia, thereby warming the region. In addition, the early autumn Mediterranean cyclone is cooling SAT in the northern region of Saudi Arabia. The SAT of the northern region of Saudi Arabia may be influenced by the subtropical high pressure thereby cooling the region.

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