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The spatial pattern of summertime subtropical anticyclones over Asia and Africa: A climatological review

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ABSTRACT: The National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) monthly mean reanalysis dataset has been used to analyze spatial variations of summertime subtropical anticyclones over the Asia–Africa region. The geopotential height and zonal wind components of 1000, 500, 200, and 100 hPa in a 30-year period (1971–2000) have been used to determine the spatial and temporal variations of the anticyclone centres, their monthly frequency and latitudinal axis variations during April–October.

The results revealed that there is a clear difference in the location of the summer anticyclone centres in lower, middle and upper levels of the troposphere. In the lower levels, the Azores subtropical anticyclone is located at the east of North Atlantic. In the middle levels, the frequencies of anticyclone centre are concentrated over the northwest of Africa, Arabian Peninsula and Iranian Plateau. In the upper troposphere, the geographical location of the anticyclone centres and their frequencies in the summer season exhibit a scattered pattern from south of China up to western Iran at 200 hPa, and a bimodal pattern over the Tibetan and the Iranian Plateaus at 100 hPa. In fact, in the entire study domain, the Iranian Plateau is a preferable location of the middle and upper troposphere anticyclones.

The highest observed latitude of the subtropical anticyclone at 100, 200 and 500 hPa levels have been seen over north of Tibetan plateau, a large area from east to west of Asia and Iran during August, July–August and July, respectively. The maximum monthly variation in the latitude of the ridgeline is seen at 500, 200, and 100 hPa from June to July which goes even up to 10 degrees at some longitudes. Copyright © 2009 Royal Meteorological Society

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1. Introduction

Examining the large scale atmospheric circulation reveals belts of the anticyclones or high pressures around 30 degrees north and south of the equator, referred to as belts of subtropical anticyclone. The existence of mountains, air-sea interaction, land surface processes, land-sea contrast etc. changes the energy budget of the atmosphere, and breaks the belts into discrete subtropical anticyclones (Wu *et al*., 2004). These cells or anticyclone centres cover huge areas over the continents in the lower stratosphere and upper and middle troposphere during summer and they are the main climatic component of these regions. Their spatial and temporal variations are associated with abnormal regional or global circulations and weather and climate disasters, causing great damages in social economy and human life. Because of their influence, many scientists have studied the different aspects of the subtropical anticyclones. One of the main aspects in studying these anticyclones is the investigation of their spatial and temporal distribution in various levels of troposphere. In one of these studies, Mason and Anderson (1963) examined the daily synoptic weather charts at 100 and 50 hPa from July 1957 to June 1959 and found that the Asian summertime 100 hPa anticyclone is the most intense and persistent circulation in the Northern Hemisphere at this pressure level. They emphasized that its influence extends from the Atlantic coast of Africa across southern Asia to the Pacific Ocean. Using the mean geopotential height for August over 9 years, Neyama (1968) studied the morphology of the subtropical anticyclone of the Northern Hemisphere. He investigated the tropospheric subtropical anticyclones over Northern Hemisphere continents and oceans and concluded that they have not coincided with each other in different levels of troposphere. In 1970s and 1980s, with the increasing studies of summertime Monsoons of south and southeast Asia, summertime subtropical anticyclones were investigated in several studies as one of the main part of summer Monsoon circulation system (Flohn, 1957; Krishnamurti, 1971a; Krishnamurti *et al*., 1973; Gao, 1981; Yeh, 1981, 1982; He *et al*., 1987). These studies noticed the formation and structure of upper-troposphere subtropical anticyclones and their role on the monsoon system evolution. Although these

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studies were considered for various aspects of subtropical anticyclones, they were mainly done for a case study and in a short time scale. Moreover, most of the studies basically concentrated on the South Asian High.

In 1980s, the climatological studies of subtropical anticyclones became possible by using grid data and applying objective methods. In one the first climatological studies, Bell and Bosart (1989) by using 15 years (1963–1977) of geopotential height data with 2.5° horizontal resolution, studied the 500 hPa closed anticyclones in the Northern Hemisphere, and indicated that in summer they have distinct maxima over the southwestern United States, northwestern Africa, southern Iran, the Tibetan Plateau and southeastern China where intense surface heating is common. Sahsamanoglou (1990) focused on spatial and temporal changes of Atlantic centres of action based upon monthly and annual mean sea level pressure values from 1873 to 1980. His analysis was primarily concerned with changes in the magnitude and location of the highest central pressure of the North Atlantic subtropical high. His general results showed that the anticyclone migrates in a somewhat elliptical pattern from month to month within an area bounded by 25°–40 °N and 20°–50 °W. Also, Davis *et al.* (1997) studied the spatial and temporal variability of Azores high over the period from 1899 to 1990 and recognized the different spatial patterns of it during summer and winter. Similar works have been done for the Southern Hemisphere subtropical anticyclones in the lower troposphere (Jones and Simmonds, 1994; Sinclair, 1996). These studies investigated the frequency and position of formation and dissipation of Southern Hemisphere anticyclones during the year. Results showed that during summer there is a tendency for highs to form near the southern regions of the three subtropical continents and to decay in eastern regions of the ocean basins.

Employing pentad averages from 1980 to 1994, Zhang *et al.* (2002) examined South Asian High activities at 100 hPa during boreal summer. Their result emphasized the relation between the formation of summertime subtropical anticyclones and the mountains as the elevated heat sources. They pointed to bimodality in South Asian High activities that is classified into the Tibetan mode and the Iranian mode and concluded that the formation of the Tibetan mode is associated with the diabatic heating over the Tibetan Plateau and the Iranian mode is associated with the adiabatic heating in the free atmosphere, as well as the diabatic heating over the Iranian plateau. Examining the seasonal variation of the South Asian High, Qian *et al.* (2002) supported the conclusions reached by Zhang *et al.* (2002) and estimated the location of the South Asian High in relation to maximum seasonal heating. From the analysis of the temporal and spatial variations of South Asian High, they found that its centre always moves towards the relatively large-valued areas of the heating rates and thus has a heat preference.

In a recent investigation, Galarneau *et al.* (2008) examined the 54-year climatology (1950–2003) of the closed subtropical anticyclones in the subtropics and midlatitudes at 850, 500, and 200 hPa. Their results showed that closed anticyclones at 200 hPa occur preferentially over subtropical continents during summer, while 500 hPa closed anticyclones form over subtropical oceans all over the year and over subtropical continents only during summer.

In one of the few studies about the Iran subtropical anticyclone in southwest Asia, Hejazizadeh (1993) employed synoptic charts at 500 hPa, to investigate the spatial locations of the northern and eastern margins of summertime subtropical anticyclones over Iran, their relationship with the polar vortex, and their influence on Iranian rainfall. She identified 5840 gpm contour as the indicator of subtropical anticyclone presence over Iran.

This research was conducted because, in our view the climatology of summertime subtropical anticyclones over Asia and Africa is as yet incompletely documented. For example, how do subtropical anticyclones vary spatially and temporally over the Asia and Africa? Do the geographical locations of the subtropical anticyclone over Asia and Africa at different levels of troposphere coincide with each other?

To help answer these questions, this study of subtropical anticyclones was undertaken with the following objectives:

(1) To develop a climatology of anticyclones over the summer subtropical Asia and Africa
(2) To investigate the monthly and spatial variations in the horizontal of summer subtropical anticyclones
(3) To investigate the geographical coincidence of summer subtropical anticyclones at different levels of the troposphere.

By identifying and describing these details we hope to promote a more comprehensive understanding of summertime anticyclones over Asia and Africa.

2. Data and methodology

An objective method is used to investigate the spatial and temporal variations of summertime subtropical anticyclones over Asia and Africa. The dataset used in this study is the 2.5° × 2.5° National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis dataset (Kalnay *et al.*, 1996) for the 30-year period (1971–2000). The Horizontal resolution is not sufficient for mesoscale studies, but it is enough for this study's purpose.

To identify the spatial and temporal variations of the anticyclone centres, we used the monthly mean values of the geopotential height and zonal wind component in lower (1000 hPa), middle (500 hPa), and upper (200 and 100 hPa) troposphere. Regarding the upper troposphere anticyclones studies, some researchers have chosen 200 hPa level (Krishnamurti *et al.*, 1973; Krishnamurti and Bhalme, 1976; He *et al.*, 1987; Galarneau *et al.*, 2008), while some other researchers have chosen 100 hPa level (Mason and Anderson, 1963; Qian *et al.*, 2002; Zhang *et al.*, 2002). The former researchers have just referred to an anticyclone over the Tibetan plateau, while the latter researchers have recognized two anticyclone centres over the Tibetan plateau and Iranian plateau. Because of the different result in the spatial variation of subtropical anticyclones at two levels, we chose both of them in the present study and compared the results. The anticyclones are investigated over a 7-month period, from April to October, to cover the transient months as well as the summer months. The research domain is confined between 60 °W–120 °E and 0°–45 °N. It is determined on the basis of analyzing the long term geopotential height and relative vorticity fields at 1000, 500, 200 and 100 hPa levels in April–October months.

The following procedures are done for the research:

A large scale view of subtropical anticyclones is presented for the seasonal and monthly time scales at different levels. The seasonal and monthly mean values of geopotential height and relative vorticity are used for April–October. The maximum negative values of relative vorticity are used as an additional variable for the recognition of summertime subtropical anticyclones. In fact, distinction of anticyclone centres is much easier by using both relative vorticity and geopotential height because increased negative vorticity is not necessarily associated with closed vortices (Hoskins and Hodges, 2002). Sometimes, the increase of wind shear lead to large negative vorticity values, while geopotential height values remained low and by using the vorticity thresholds alone, it is possible that such a structure would be mistaken an anticyclonic vortex (Luo and Dai, 2008). However, the negative vorticity field can help in recognizing the small scale anticyclonic structures (Hoskins and Hodges, 2002). For example, it is a suitable criterion for distinguishing Iran anticyclone centre at mid-troposphere (Zarrin, 2008). Relative vorticity values are expressed in units of second^{-1} and are calculated as:

$$\zeta_r = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$$

In order to study the spatial and temporal variations of subtropical anticyclones, monthly (April–October) and seasonal (JJA) frequencies of anticyclone centres are investigated by counting the number of occurrences of the anticyclone centre over a particular grid-point in a given month during 30-year period (1971–2000). Depending on the number of anticyclone centres found in each month, the sum of the monthly frequency of anticyclone centres will be 30 if only one anticyclone centre is registered, and will be more if more than one centre is registered in a given month.

Generally, the maximum geopotential height is the most common criteria for identification of the anticyclone centre (Zhang *et al.*, 2002). Based upon the above criterion, in this research the centre of anticyclone is found at a grid point where the geopotential height is the greatest compared to the adjacent grid points. Therefore the location of anticyclonic centre can be expressed by the latitude and longitude coordinates of the point. It is to be noted that if more than one grid point represents the maximum height value, then two or more centres are considered as anticyclone centres when the difference in geopotential height between the adjacent grid points is larger than 10 gpm.

For recognizing the latitudinal location of subtropical anticyclones and clarifying the zonal continuity/discontinuity of them in different levels and at different times, we used the ridgeline concept. The coincidence of the anticyclones in the vertical can also be investigated through the study of ridgeline. The ridgeline of the subtropical anticyclone is defined as the interface between the easterlies and westerlies (Zhang *et al.*, 2002). In other words, the anticyclone ridgeline is defined as a place where zonal wind component is zero and the meridional variation is positive above the ridgeline and negative below it. In fact, the meridional wind component vanishes at the latitude where the zonal mean centre of the subtropical anticyclone is located. Thus in both the free atmosphere and the planetary boundary layer, the location of the ridge of the subtropical anticyclone in the sense of zonal mean can be defined from the zonal wind distribution by using the following criteria (Liu and Wu, 2004; Wu *et al.*, 2004):

$$\begin{cases} (a) \quad u = 0; & \text{and} \\ (b) \quad \partial u \big/ \partial y > 0 & \text{In Nortern Hemisphere} \end{cases}$$

The anticyclones are elongated in the approximately East–West direction with strong easterlies and westerlies, it is thus enough to identify the anticyclonic circulation using the sign of du/dy. Using this criterion we will be able to recognize the large scale latitudinal axis of subtropical anticyclones.

3. Results and discussion

3.1. The mean position of the subtropical anticyclone

The 30-year mean geopotential height (1971–2000) and 1000 hPa vorticity during the summer months (June–July–August) shows the location of the anticyclone cell in the eastern North Atlantic. As can be seen in Figure 1(a), the main axis of the anticyclone is at 35 °N and it shows a strong southwest–northeast tilt in the eastern North Atlantic. This anticyclone is known as the Azores High and the mean geopotential height of its centre reaches to 210 gpm (around 1025 hPa). In fact, in the considered region at the lower levels the Azores high pressure cell is the only anticyclone during the summertime. The relative vorticity at its centre reaches about −0.9e−6 s^{-1}, which is an indication of intense anticyclonic circulation in the region (Figure 1(a)). However, the increase of wind shear within some regions of the Mediterranean Sea and northern Indian Ocean lead to increased negative vorticity values, while geopotential

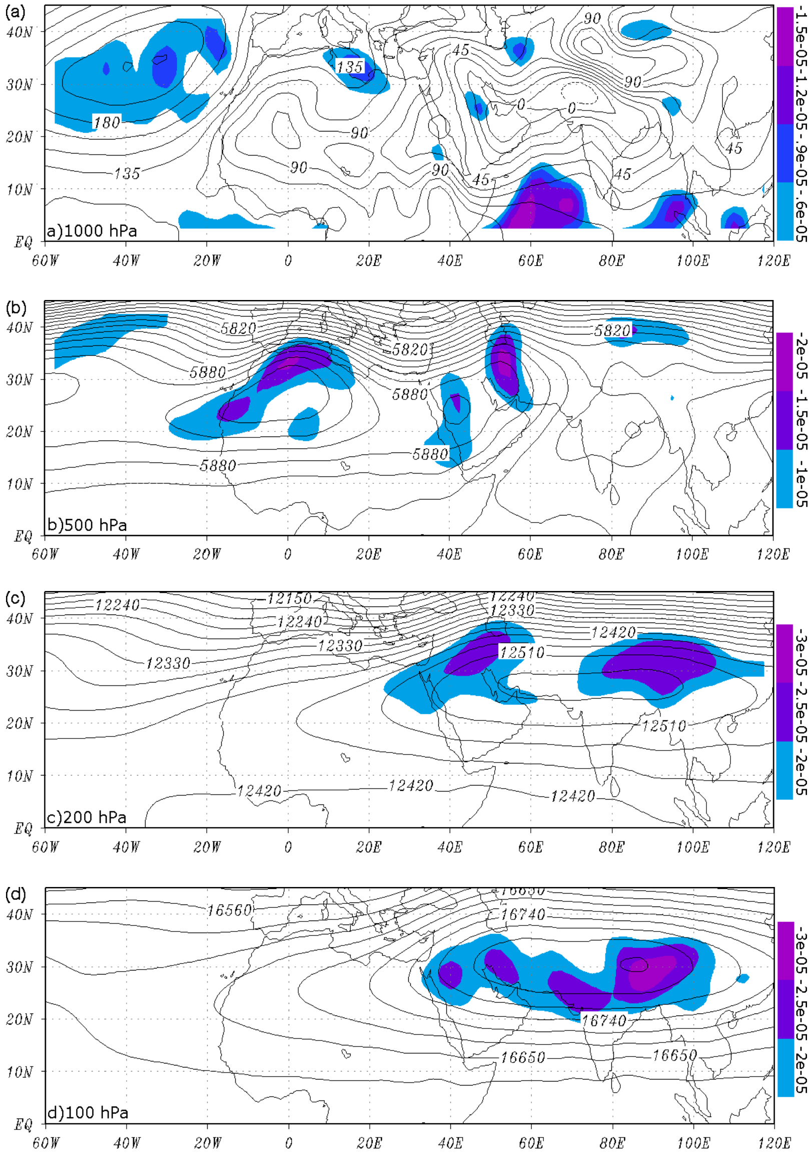

Figure 1. Mean geopotential height and negative relative vorticity for summer (June–July–August) in 30 years (1971–2000) period, at (a) 1000 hPa, (b) 500 hPa, (c) 200 hPa and (d) 100 hPa. Unit for geopotential and vorticity are gpm and s^{-1} respectively. This figure is available in colour online at www.interscience.wiley.com/ijoc

height values remained low. As it is mentioned in data and methodology section, such a structure is not necessarily associated with the closed vortices (Hoskins and Hodges, 2002).

Figure 1(b) shows the summer mean geopotential height and negative relative vorticity at 500 hPa. It is seen that the subtropical anticyclone at 500 hPa has two centres. One is situated over the northwestern Africa with 5910 gpm and the other one, which is smaller, is located over the Arabian Peninsula with 5890 gpm. Examining vorticity at this level also shows that these regions experience high negative vorticity values in summer. Additionally, there is also a maximum negative vorticity region over western Iran. It is interesting to note that at 500 hPa, vorticity over Iran reaches to the value of $-2e-5s^{-1}$ which is similar to northwestern Africa and it is more negative than the value over Saudi Arabia. Inspecting the mean seasonal geopotential height at this level reveals that there is no independent anticyclone cell over Iran, and that a tongue of high pressure cells from Africa and Saudi Arabia has extended over Iran; nevertheless, the existence of stronger negative vorticity along with more intense anticyclonic circulation is evidence for a different atmospheric circulation pattern over Iran. Furthermore, the recent researches showed that the Zagros Mountains as an elevated heat source plays the main role in the formation and reinforcement of subtropical anticyclones over Iranian plateau (Mofidi, 2007; Zaitcheck *et al.*, 2007; Zarrin, 2008). In the following sections, it can be seen that this high negative vorticity region is associated with a high frequency of subtropical anticyclone centres in summer.

The 200 hPa geopotential height field (Figure 1(c)) shows a vast high pressure cell over south Asia that is to the west has extended toward northern Central Africa. The anticyclone axis is located at about 27 °N with geopotential height at its centre exceeding 12 540 gpm. However, maximum negative vorticity of $-2.5e-5\ s^{-1}$ is seen over two regions which are far from the anticyclone centre: west of Iran to southern coast of Caspian Sea and over the northeastern Tibetan Plateau. It seems that the meridional temperature gradient and the increased wind shear associated with the subtropical jet stream cores (Krishnamurti, 1971b; Lin and Lu, 2005) are responsible for such a high negative vorticity in the aforementioned regions.

Figure 1(d) shows the mean summertime geopotential height and maximum negative vorticity values at 100 hPa. The anticyclone which is seen over south Asia is the strongest and largest anticyclonic circulation system among all investigated levels. In comparison to 200 hPa, at this level the anticyclone axis has shifted toward northern latitudes and reaches to 30 °N. 16 800 gpm contour as the central cell of the anticyclone has covered the area from east of Tibetan Plateau to west of Iran. A small cell with 16 830 gpm at its centre is also seen over Tibetan Plateau east of 80 °E. Examining the vorticity pattern at this level indicates that unlike the 200 hPa level, the most intense anticyclonic circulation and maximum negative vorticity coincides well with the main subtropical anticyclone cell. As such, negative vorticity less than $-2e-5\ s^{-1}$ influences from east of Tibetan Plateau to west of Middle East and its maximum value can be seen over Tibetan plateau, northwest of India, southwest of Iran and north of Arabian Peninsula (Figure 1(d)).

In general, examining the geopotential height and maximum negative vorticity fields reveals obvious differences between the patterns of anticyclone centres at the surface, middle, and upper troposphere. Moreover, the observed differences of 100 and 200 hPa, especially in vorticity field, make it necessary to study both levels in the following sections in order to achieve a comprehensive view.

To explore the monthly mean pattern of the subtropical anticyclone, the monthly mean of geopotential height and vorticity from April to October at 1000, 500, 200, and 100 hPa levels were examined. Because of the large number of maps and page limitations, a summary of the results are shown in Tables I and II.

The anticyclone centre at 1000 hPa for all months is located over the Atlantic (Table I). There is a longitudinal

Table I. Geographical characteristics of the 30-years (1971–2000) mean of subtropical anticyclone centre and its associated relative vorticity at 1000 and 500 hPa. The letters in parentheses indicate the cardinal and ordinal directions.

Level	Month	Characteristics of anticyclone centre				Relative vorticity			
		Hgt (gpm)	Location	Lat (°)	Lon (°)	Vorticity ($\times 10^{-5}\ s^{-1}$)	Location	Lat (°)	Lon (°)
1000 hPa	Apr	193.8	Atlantic(N)	33.7	−35.0	−1.26	Bay of Bengal	15	87.5
						−1.33	Arabian Sea	17.5	65
	May	204.4	Atlantic(N)	34.0	−35.7	−1.30	Saudi Arabia	25	50
						−0.974	Atlantic(N)	32.5	−30
	Jun	214.4	Atlantic(N)	33.7	−35.7	−1.34	Saudi Arabia	25	47.5
						−1.05	Atlantic(N)	32.5	−30
	Jul	224.6	Atlantic(N)	35.2	−38.0	−1.26	Atlantic(N)	37.5	−17.5
						−1.26	Atlantic(N)	32.5	−30
	Aug	208.4	Atlantic(N)	35.2	−36.7	−1.20	Atlantic(N)	37.5	−17.5
						−1.15	Atlantic(N)	32.5	−30
	Sep	193.6	Atlantic(N)	35.5	−31.3	−1.17	Saudi Arabia	25	47.5
						−0.95	Atlantic(N)	25	−22.5
	Oct	189.0	Atlantic(N)	35.4	−34.3	−1.19	East Asia	22.5	112.5
						−1.18	Saudi Arabia	25	47.5
500 hPa	Apr	5876.5	Saudi Arabia	15.3	51.4	−0.215	East Asia	17.5	112.5
		5874.1	Africa(W)	15.7	2.5	−1.77	India	20	80
						−1.79	Africa(W)	17.5	−2.5
	May	5890.0	Saudi Arabia	20.6	49.1	−2.10	Saudi Arabia	22.5	45
		5892.4	Africa(W)	18.4	1.8	−1.88	Africa(W)	22.5	10
	Jun	5892.6	Saudi Arabia	25.4	48.3	−2.35	Iran	30	57.5
		5917.5	Africa(W)	24.1	4.9	−2.17	Saudi Arabia	25	42.5
						−1.88	Africa(W)	27.5	−12.5
	Jul	5893.7	Iran(SW)	30.8	50.3	−2.69	Iran	35	52.5
		5937.3	Africa(NW)	30.3	−1.1	−2.52	Africa(W)	32.5	0
	Aug	5898.7	Iran–Iraq	28.9	46.0	−2.43	Iran	35	52.5
		5931.7	Africa(NW)	30.3	−1.4	−2.56	Africa(W)	32.5	−2.5
	Sep	5895.9	Saudi Arabia	26.1	41.0	−1.79	Iran	30	55
		5900.4	Africa(NW)	25.5	−7.8	−2.12	Saudi Arabia	27.5	42.5
	Oct	5881.8	Saudi Arabia	21.7	49.3	−1.83	East Asia	22.5	112.5
		5877.4	Africa(W)	20.7	−18.6	−1.55	Oman Sea	25	57.5
						−1.65	Saudi Arabia	27.5	45

Table II. As in Table I but for 200 and 100 hPa levels.

Level	Month	Characteristics of anticyclone centre				Relative vorticity			
		Hgt (gpm)	Location	Lat (°)	Lon (°)	Vorticity ($\times 10^{-5}$ s^{-1})	Location	Lat (°)	Lon (°)
200 hPa	Apr	12465.7	Asia(SE)	11.8	115.7	−3.11	Asia(SE)	20	107.5
		12438.7	Africa(E)	2.7	35.6	−3.23	Africa(N)	17.5	20
		12462.9	Africa(W)	1.4	−7.9				
	May	12491.4	Vietnam	17.3	105.2	−2.37	Vietnam	22.5	105
		12468.3	Africa(W)	6.3	−15.0	−3.05	Africa(W)	17.5	−2.5
	Jun	12536.9	Myanmar(N)	24.5	96.8	−3.30	Myanmar(N)	30	97.5
		12529.4	Iran(SE)	25.6	62.1	−3.30	Iran(W)	30	47.5
	Jul	12572.0	Tibetan plateau	28.8	87.5	−3.16	Tibetan plateau	32.5	85
		12578.8	Iran(E)	30.2	59.3	−3.31	Iran(N)	37.5	50
	Aug	12572.5	Tibetan plateau	29.2	86.7	−3.13	Tibetan plateau	35	87.5
		12564.5	Iran(E)	29.6	62.3	−3.23	Iran(NW)	37.5	47.5
	Sep	12508.3	Tibetan Plateau(SE)	25.4	91.1	−3.35	Tibetan Plateau(E)	32.5	95
		12511.6	Iran(S)	25.8	57.5	−2.70	Iran(W)	30	45
	Oct	12473.6	Asia(E)	19.2	113.8	−3.39	Myanmar(N)	25	97.5
		12455.9	Arabian Sea	18.0	61.0				
100 hPa	Apr	16642.7	Central India	13.3	104.1	−2.02	Thailand	17.5	102.5
		16655.9	Africa(W)	0.4	−10.2	−1.78	Central India	20	80
		16629.9	Africa(E)	7.5	51.2	−2.41	Africa(N)	17.5	10
	May	16699.1	Myanmar	20.9	96.1	−2.2	Asia(E)	25	112.5
		16668.1	Guinea Gulf	7.0	0.3	−2.3	Tibetan plateau(SE)	27.5	92.5
						−2.3	Africa(W)	17.5	2.5
	Jun	16798.6	Tibetan plateau	28.3	88.8	−3.50	Tibetan plateau	27.5	90
		16794.2	Afghanistan(S)	28.0	65.5	−2.84	India(NW)	22.5	75
						−2.70	Central Iran	30	55
	Jul	16867.5	Tibetan Plateau	31.4	86.1	−3.41	Tibetan plateau	30	87.5
		16871.0	Iran(E)	33.3	57.9	−3.13	Pakistan(E)	25	70
						−2.83	Central Iran	32.5	50
	Aug	16844.9	Tibetan Plateau	31.6	85.0	−3.16	Tibetan plateau	30	85
		16849.7	Iran(E)	32.0	59.1	−3.04	Pakistan(E)	25	70
						−2.75	Central Iran	30	52.5
						−2.87	Syria–Jordan	30	40
	Sep	16741.9	Tibetan Plateau	28.0	88.8	−3.17	Tibetan plateau	27.5	87.5
		16734.7	Pakistan	27.8	68.8	−2.58	India(NW)	22.5	75
	Oct	16652.7	Myanmar(E)	21.6	98.8	−2.38	China(E)	25	115
		16616.0	Guinea Gulf	8.5	14.5	−2.65	Tibetan plateau	25	92.5

as well as a latitudinal shift in the position of the height centre as the season progresses. In July the centre has moved to the north but also to the west of its April position, while in October it stays at the same latitude as July but moves east. Examining the maximum relative vorticity values in this level, it is seen that the maximum negative relative vorticity centre over Saudi Arabia (25 °N/47.5 °E) present in May, June, September and October is a persistent centre and is stronger for these months than the eastern Atlantic centre (32.5 °N/30.0 °W) (Table I). Although the anticyclonic centre is located over the Arabian Sea in April, during May and June with a west–northwestward shift, it moves toward Saudi Arabia. As Table I shows the anticyclonic centre disappears in the lower troposphere in peak summer (July–August) and in September, it appears again in its June position. It seems that the disappearance of lower tropospheric anticyclonic centre in peak summer is in relation to the surface heating over southwest Asia. It's interesting that maximum negative vorticity is mainly seen over the southwest Asia during transient months (April–May and September–October) and in peak summer it is only seen over the eastern Atlantic Ocean (Table I).

At 500 hPa, there is a southwestward displacement of the African height centre from June to October. In this level, the Iran vorticity centre (around 30 °N/57.5 °E) is stronger for most months than the north African centre. However, the reverse happens with the height centres, the Saudi Arabia and Iran height centres are weaker from June to September than the north African height centre (Table I).

At 200 hPa, in the summer months (JJA), the vorticity centre over Iran is stronger than the centre over Tibetan plateau. However, in the height field, the two centres are of similar amplitude. Also, in this level for both the Iran and the Tibetan regions, the vorticity centres are consistently (July, August, and September) located 5–7° to the north of the corresponding height centres (Table II).

At 100 hPa, there is a shift of the anticyclone centre from the Myanmar region to the Tibet–Iran region and back again, as the season proceeds from spring to summer to autumn. In the summer months (JJA), the Iran and the Tibet height centres have similar strength. However, the Tibet vorticity centre is consistently stronger than the Afghanistan and Iran vorticity centres for months JJA and for September (Table II).

3.2. Frequency of the subtropical anticyclone centre

To investigate the variation in geographical location of the subtropical anticyclone, the frequency of its centre during 30-year (1971–2000) in the domain of the study was determined. To characterize the monthly displacement of the anticyclone centre location especially during transient months from spring to summer and also to autumn more clearly, the last two months of spring (April–May) and the first two months of the autumn (September–October) were also examined.

At 1000 hPa, there is only one anticyclone centre for each month regarding to the maximum geopotential height in the entire study domain, so the sum of frequencies for each month is 30. However, at the other levels, the sum of frequencies for each month is more that 30 and depends on the number of anticyclone centres which has been found for that month. For example, the frequency of anticyclone centres in July is 60, 37, and 43 at 500, 200, and 100 hPa levels, respectively (Table III).

The highest frequencies of high pressure centres at 1000 hpa (Figures 2(a)–(h)), is located in the region confined to 25–60 °W longitude and 25–45 °N latitude from April through October. Moreover, it is seen that the anticyclone centre at this level unlike other levels possesses permanence in terms of geographical location over the eastern North Atlantic.

Geographical location of the anticyclone at 500 hPa level is varying in a region from 40 °W to 70 °E. Frequency of the anticyclone centre during the transient months of September and May is fairly similar and its geographical location is mainly over west and Central Africa and the Arabian Peninsula. During the warm season the anticyclone centre is shifted toward higher latitudes (especially over Africa) and in addition to the west and Central Africa and the Arabian Peninsula, another anticyclone centre is seen over Iran (Figure 3(a)–(g)). Existence of this anticyclone centre explains high values of negative vorticity at 500 hPa level (as explained in the previous section) over Iran (Figure 1(b)).

Examining the anticyclone centre frequency at 200 hPa level indicates that during April, the subtropical anticyclone is located in the Southeast Asia over China Sea (Figure 4(a)), while in May it is located over Indo–China (Figure 4(b)), and from June it moves toward northwesterly (Figure 4(c)). During July and August the anticyclone centrecentres reach their farthest location toward the north and extend from the eastern Tibetan Plateau to the western Iran, north of 30 °N (Figure 4(d) (e)). During September and October the anticyclone centres return to the southern latitudes (Figure 4(f) (g)).

Examining the frequency of the anticyclone centre at 100 hPa level shows that during April the geographical position of the anticyclone centre is scattered from Southeast Asia to Guinea Gulf (Figure 5(a)). As it is seen from Figure 5(b), during May the anticyclone centre is mostly located over Southeast Asia (Indochina and Myanmar) and from June to August it is shifted toward higher latitudes and another centre is seen over eastern Iranian Plateau (Figures 5(c)–(e)). It is interesting to note that at this level, the anticyclone centres are mainly located over specific regions and is not scattered. Tibetan Plateau and Iranian Plateau are the two regions over which the anticyclone centres are mainly located.

In September the anticyclone centre returns to the East and for the most part is located over the Tibetan Plateau (Figure 5(f)). In October the anticyclone centre is scattered but its maximum is located over Myanmar (Figure 5(g)).

Figure 6 and Table III show the sum of the anticyclone centre frequencies in summer (JJA) at 1000, 500, 200, and 100 hPa levels. The distribution of frequencies, demonstrates the concentration of anticyclone centres on particular locations during summer. With regard to Figure 6(a), the anticyclone centre frequencies have two preferable locations in eastern Atlantic Ocean during 30-year period, although the locations are very near to each other. In general, anticyclone centre of this level is located in higher latitudes, compare to the anticyclone centres of middle and upper troposphere.

Figure 6(b) and Table III show the anticyclone centre frequencies at the 500 hPa level for the summer season. As it can be seen, the anticyclone centres occur over

Table III. Frequencies of subtropical anticyclone centres for 30-years (1971–2000) in summer (June, July, August).

Level (hPa)	Atlantic Ocean			Northwest Africa			Arabian Peninsula			Iranian Plateau			Tibetan Plateau			Other regions			Sum
	Jun	Jul	Aug	Jun	Jul	Aug	Jun	Jul	Aug	Jun	Jul	Aug	Jun	Jul	Aug	Jun	Jul	Aug	JJA
1000	**30**	**30**	**30**	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	**90**
500	–	–	–	**30**	**30**	**30**	**17**	**5**	**15**	**13**	**25**	**15**	–	–	–	–	–	–	**180**
200	–	–	–	–	–	–	–	–	–	**13**	**20**	**13**	**26**	**14**	**16**	**4**	**3**	**8**	**117**
100	–	–	–	–	–	–	–	–	–	**12**	**25**	**18**	**26**	**18**	**24**	**3**	–	**1**	**127**

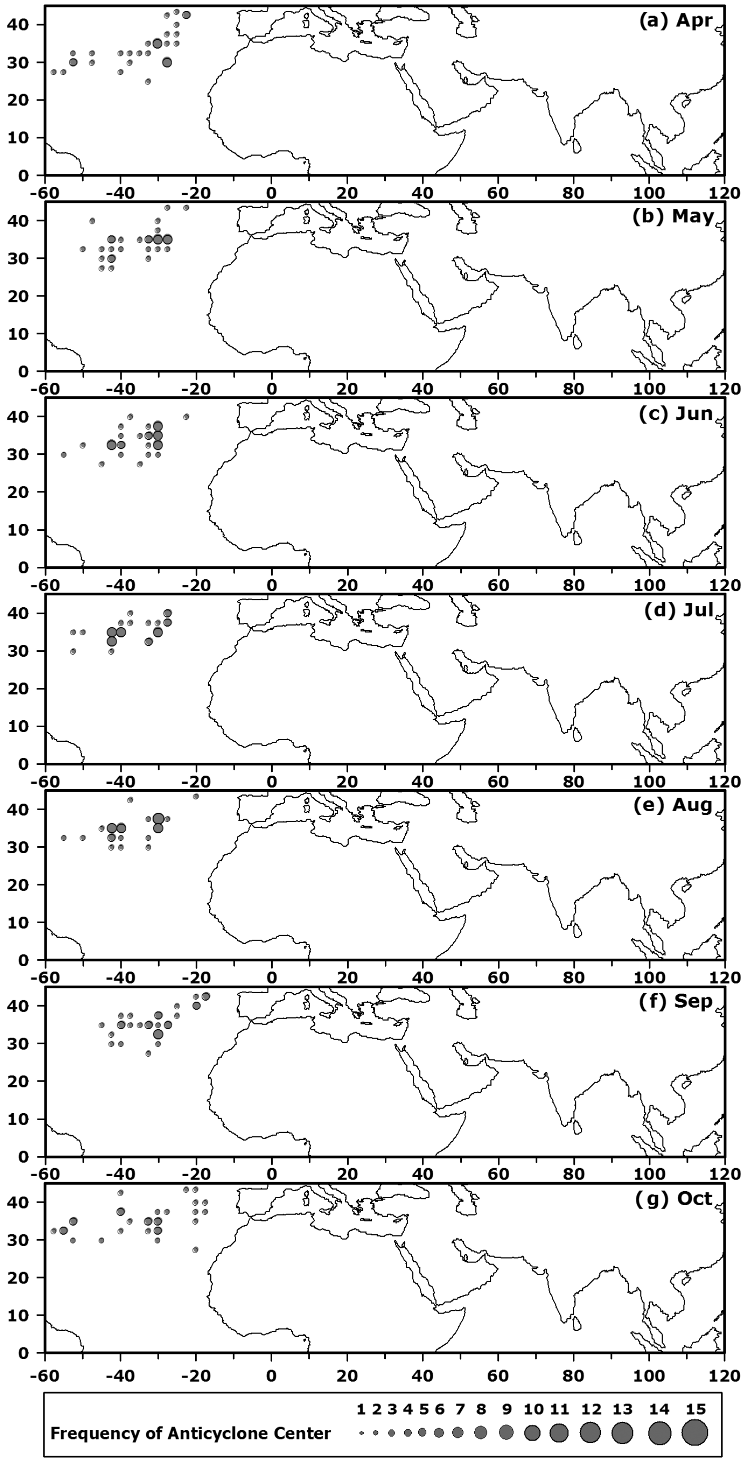

Figure 2. Frequency of the anticyclone centres over the 1971–2000 period at 1000 hPa: (a) April; (b) May; (c) June; (d) July; (e) August; (f) September; (g) October. The diameter of the circles is proportional to the frequency of anticyclone centres.

northwestern Africa, Iranian Plateau, and the Arabian Peninsula respectively. Unlike the long-term seasonal geopotential height mean (Figure 1(b)), anticyclone centre frequencies over Iran is very outstanding in 30-year period (Figure 6(b)). It is interesting that the frequency of Iran anticyclone is more than the anticyclone over Arabian Peninsula during the summer (Table III).

Figures 6(c) and (d) show the sum of anticyclone centres in summer at 200 and 100 hPa, respectively. While the spatial distribution of anticyclone centres at 200 hPa is much more uniform and widespread, there is clustering of the frequencies around particular locations at 100 hPa. Also, the summer frequencies of 100 hPa are located in higher latitude in comparison to those at 200 hPa. At 100 hPa, the subtropical anticyclone exhibits as bimodality in longitude location during the summer (JJA), one location is over the Tibetan Plateau and another over the Iranian Plateau (Figure 6(d)). In fact,

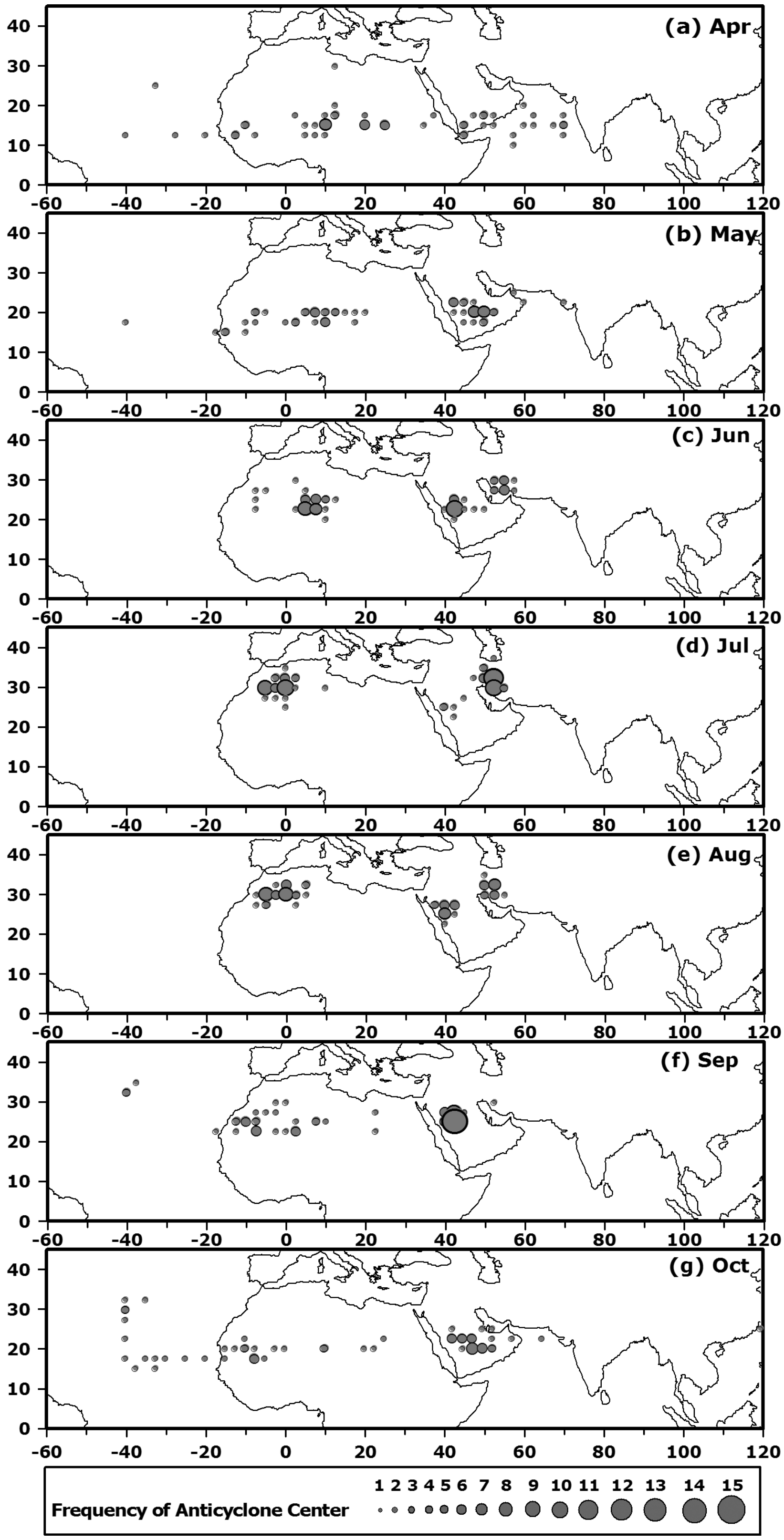

Figure 3. As in Figure 2 except for 500 hPa.

subtropical anticyclone centres possess two preferable locations corresponding to the location of the Tibetan Plateau to the east and Iranian Plateau to the west, but scarcely appear near 70–80 °E (Table III), where the centred region of the climate mean anticyclone is located (Figure 1(d)). According to its preferable location, the anticyclone can be classified into the Tibetan mode, and the Iranian mode, respectively (Zhang *et al.*, 2002). The investigation of 30-year monthly frequencies of anticyclone centres at 100 hPa shows the dominance

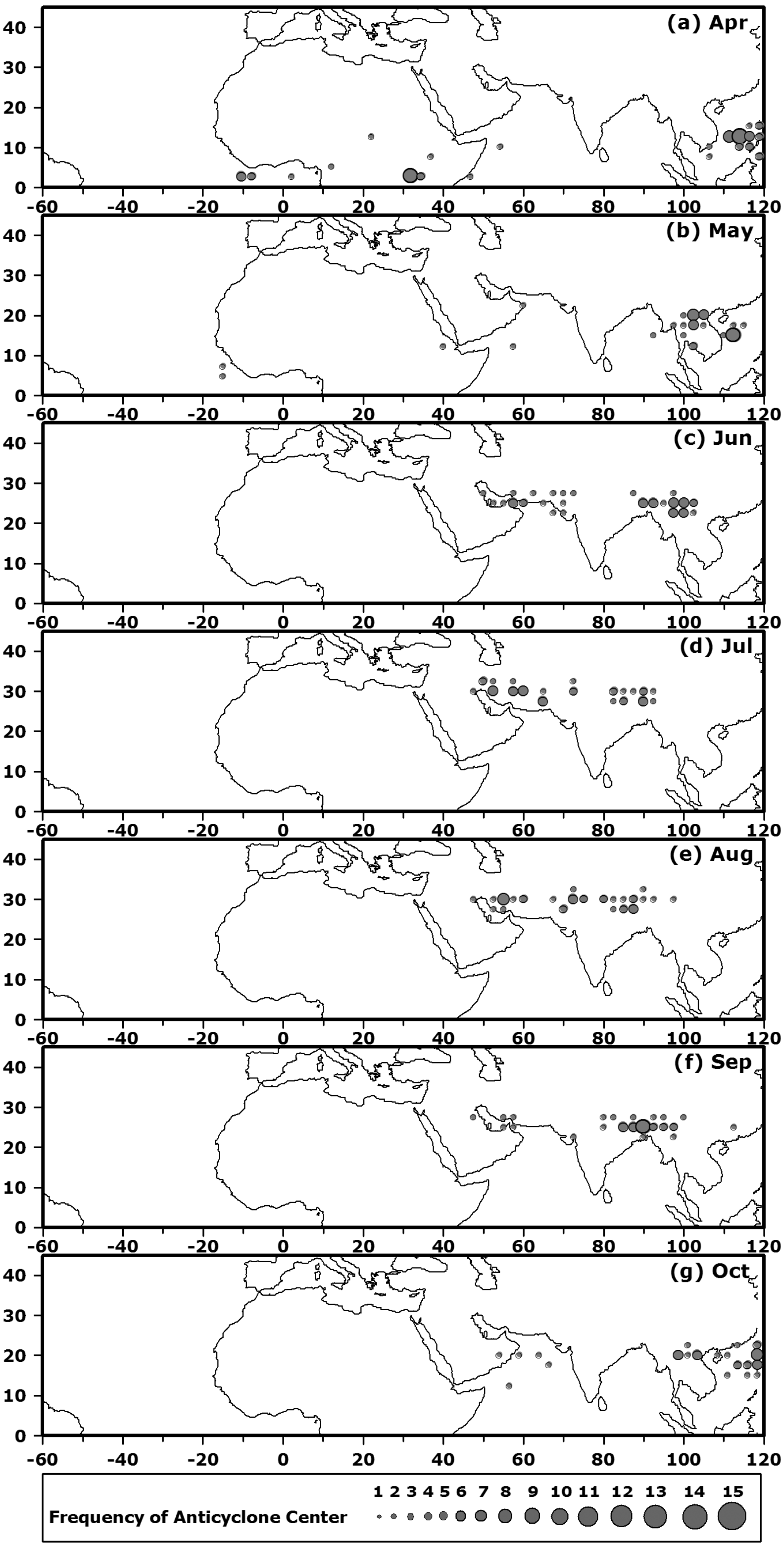

Figure 4. As in Figure 2 except for 200 hPa.

of Tibetan mode during June and September. In July, the Iranian mode is stronger than Tibetan mode and in August, both Modes show an equal frequency of anticyclone centres. Moreover, during our study period (1971–2000), the Tibetan and Iranian modes coexist in 8 months of June, 13 months of July, and 12 months of August (Figure 5 and Table III).

It is noteworthy that the Iranian plateau shows the high concentration of anticyclone centres in both middle and upper troposphere in the entire study domain during summer (Table III).

Recently, Zarrin (2008) has found that the formation of subtropical anticyclone over Iranian plateau is corresponded to the Zagros Mountain's thermal forcing

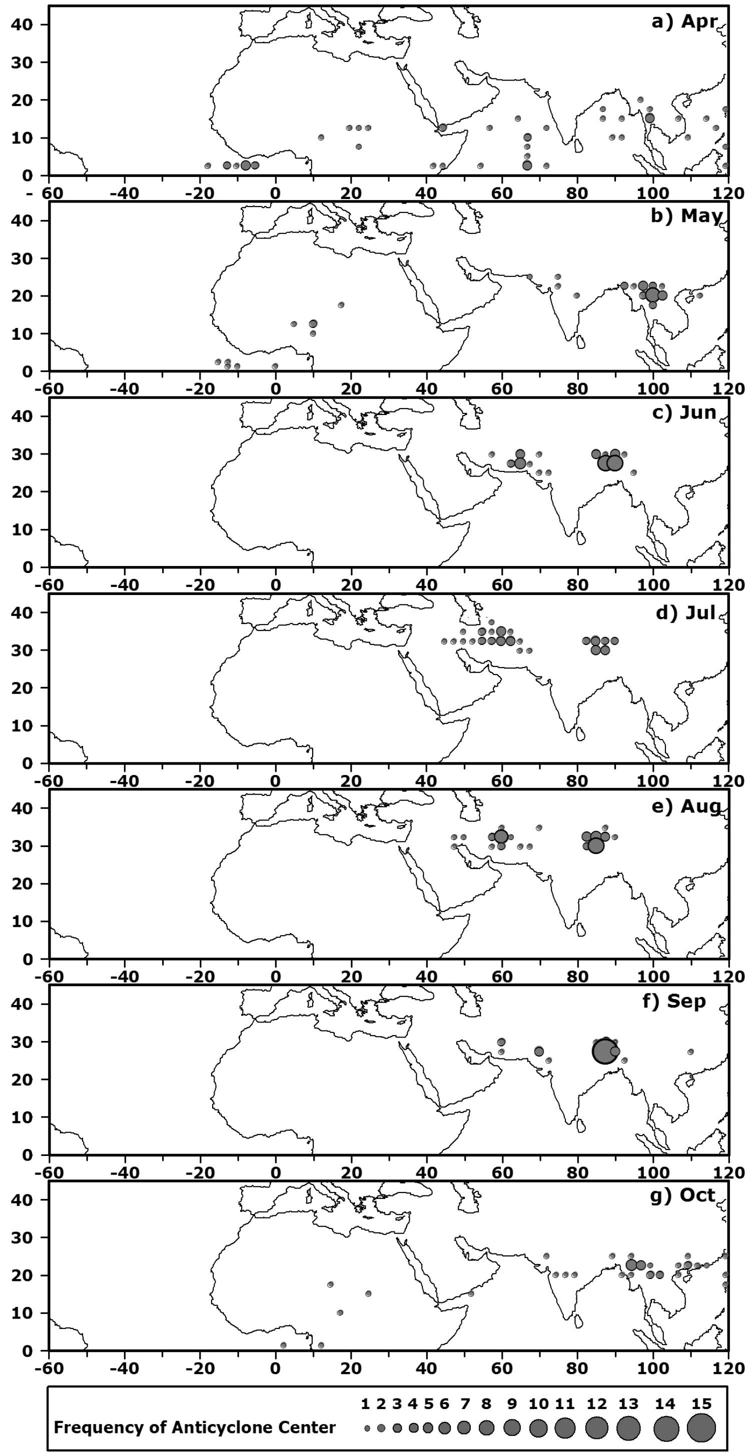

Figure 5. As in Figure 2 except for 100 hPa.

in mid-troposphere and Monsoon circulation in upper-troposphere.

3.3. Latitudinal variations of the subtropical anticyclones

The ridgeline, which represents the mean latitudinal location of the subtropical anticyclone, can be considered as a criterion for the determination of the anticyclone location and anticyclonic circulation axis. Additionally, the ridgeline can be used for determining the zonal extension of anticyclonic circulation and showed the continuity/discontinuity of anticyclone centres in subtropical regions.

Figure 7 shows the long term monthly mean of ridgeline at 1000, 500, 200 and 100 hPa. Examining the ridgeline at the 1000 hPa level shows that the ridgeline at this level has extended from 20to 60 °W and its mean position during the summer is near 32.5 °N (Figure 7(a)). At this level the ridgeline does not move much and it has a slight shift toward higher latitude during April and

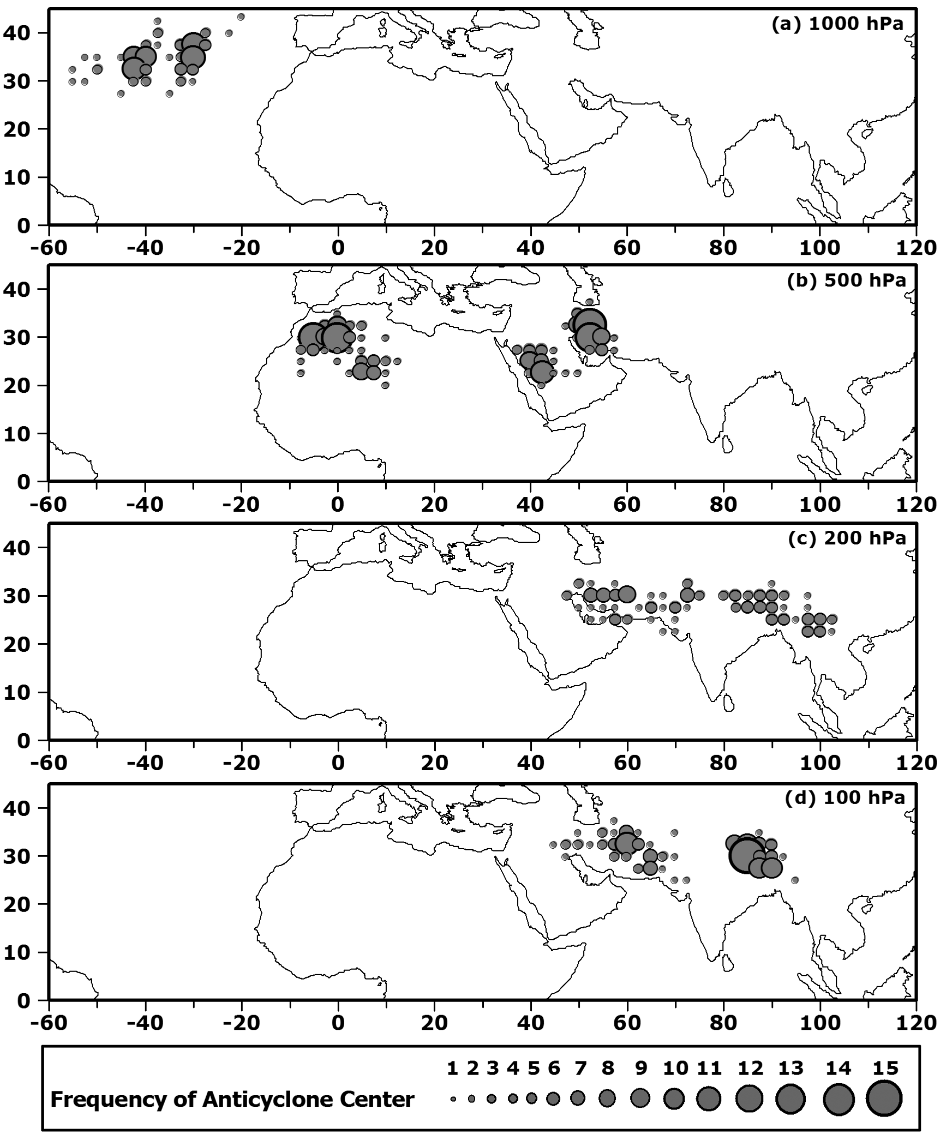

Figure 6. Sum of the Frequencies of the anticyclone centres for summer months (JJA) over the 1971–2000 period. (a) 1000 hPa, (b) 500 hPa, (c) 200 hPa, (d) 100 hPa.

August and returns to lower latitudes during September and October.

Investigating middle and upper troposphere anticyclones, it is finding that in some months the ridgeline is not continuous and has been broken at some meridians (Figure 7(b)–(d)). At the 500 hPa level the ridgeline has a sizeable longitudinal extension. Also, it ranges by around 25° (10–35 °N) in the meridional direction. The highest observed latitude of the ridgeline during the warm period of the year is at 37.5 °N over the northern Tibetan Plateau during August. The lowest latitude is around 10 °N during April. Over the northwestern Africa, Arabian Peninsula and southwestern Iran during July and August and over the Tibetan Plateau during August and May (Figure 7(b)), the ridgeline has an abrupt shift toward higher latitudes.

The subtropical anticyclone ridgeline at the 200 hPa level has an extension around 145° (25 °W–120 °E) and 25° (5–30 °N) in the east–west and south–north directions respectively. At this level the ridgeline is not continuous during May, with discontinuity over the Ethiopian Plateau (Figure 7(c)). As can be seen in the Figure, the ridgeline in the Tibetan Plateau jumps to higher latitudes during June and September.

Examining the ridgeline at 100 hPa level indicates that the ridgeline has moved toward higher latitudes when compared to its location at 200 hPa level. Also, during the months of July and August the ridgeline has extended over the whole domain of study in the east–west direction and during the rest of the months it has extended from the east of our domain of study to the African west coast. At this level, the ridgeline is discontinuous over the Indian Ocean–Horn of Africa during the month of April. In the south–north direction the ridgeline has an extension of around 22° (10–32 °N). The highest observed latitude at this level is over Iran at about 35 °N and has occurred during July (Figure 7(d)). Examining Figure 7 shows that the maximum pole-ward displacement of the ridgeline at

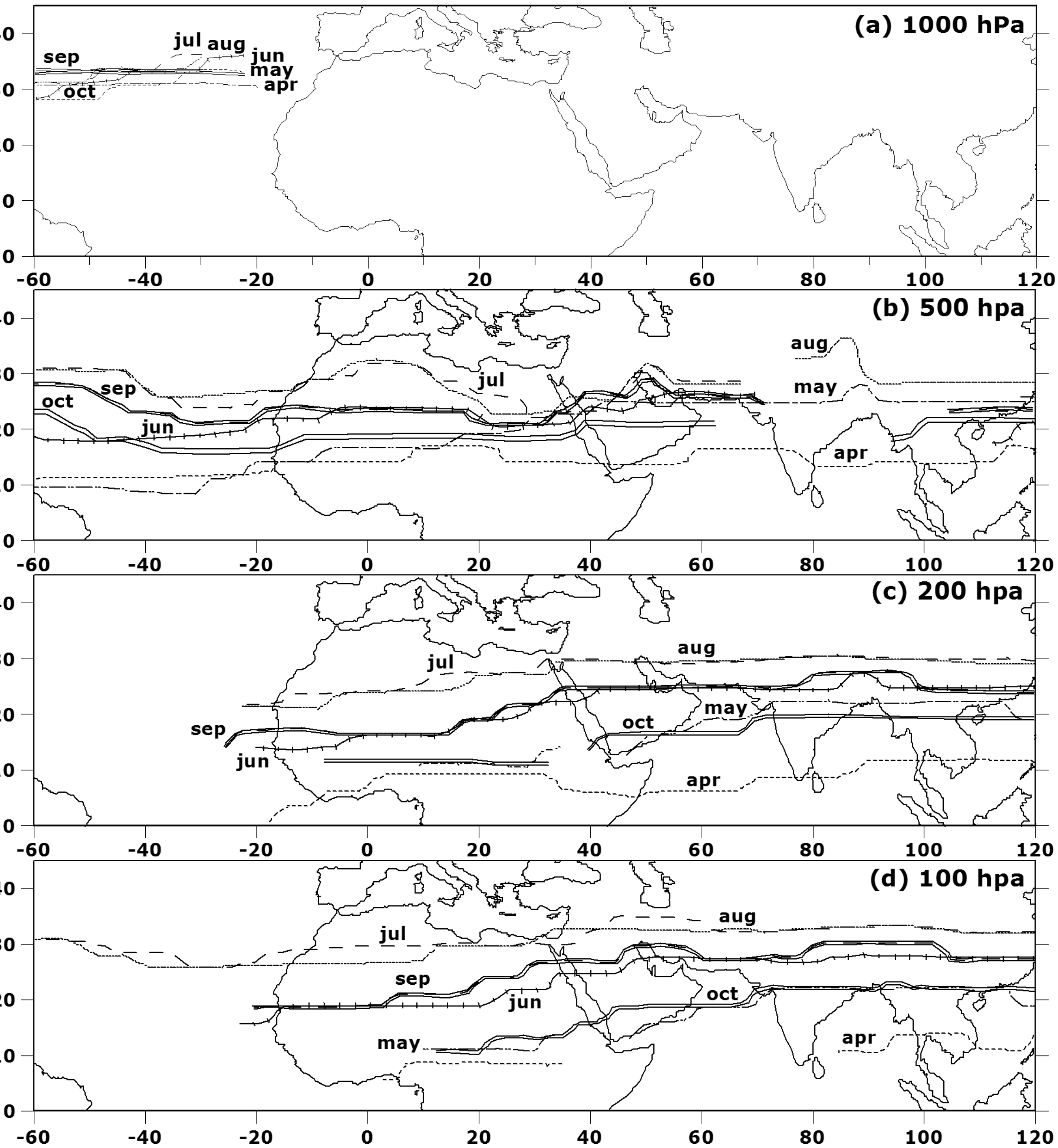

Figure 7. Monthly climatological mean position of the subtropical anticyclone ridgeline for (a) 1000 hPa, (b) 500 hPa, (c) 200 hPa, and (d) 100 hPa, in 30 years (1971–2000).

500, 200, and 100 hPa levels has occurred from June to July.

Comparing the ridgeline of different levels indicates that anticyclonic circulation over the eastern Atlantic Ocean occupies a small region in the lower troposphere (Figure 7(a)), while subtropical anticyclones of the upper troposphere forms a vast zonal belt of anticyclonic circulations in summer (Figure 7(c)–(d)). It is worth noting that the continuous and horizontal ridgeline of upper levels shows a large and elongated anticyclone during June–September, while mid-level wavy ridgeline, despite its continuity, is an indicator of more than one centre. In this regard, the ridgeline inclination toward higher latitudes over north Persian Gulf, western Arabian Peninsula and northwest Africa, indicates the anticyclone centres of Iran, Arabian Peninsula and northwestern Africa.

4. Summary and conclusion

The geographical characteristics of the subtropical anticyclone centres represent a key factor for the determination of the warm season climate over Asia and Africa.

The geographical location of the anticyclone centres and their frequencies in the summer season are located over the eastern North Atlantic at 1000 hPa, over the northwestern Africa, Arabian Peninsula, and Iran at 500 hPa, scattered pattern from south of China up to western Iran at 200 hPa, and a bimodal pattern over the Tibetan and the Iranian Plateaus at 100 hPa.

Examination of the anticyclone spatial pattern at 1000, 500, 200, and 100 hPa showed that in our domain of study (60 °W–120 °E) only the Iranian Plateau has a closed anticyclone centre both in the upper and middle troposphere (Table III). Other regions, such as the

Tibetan Plateau only in upper troposphere and northwestern Africa and the Arabian Peninsula only in middle troposphere experience closed anticyclone centres. The Azores high also develops only in the lower troposphere. This result is in contrast with the conventional view that states summertime anticyclone which is extended over Middle East and east Mediterranean is a tongue of Azores high (Snead, 1968; Lydolph, 1977; Prezerakos, 1984; Alijani, 1997; Saligheh, 2003). In fact the results show that the Azores high forms only in the lower troposphere over the eastern North Atlantic and cannot be observed in the middle and upper troposphere, whereas the Iran anticyclone develops in the middle and upper troposphere.

At 100 hPa, subtropical anticyclone centres possess two preferable locations corresponding to the location of the Tibetan Plateau to the east and Iranian Plateau to the west. According to its preferable location, the anticyclone can be classified into the Tibetan mode, and the Iranian mode, respectively. It seems that the spatial concentration of anticyclone centres at 100 hPa, compare to the 200 hPa anticyclones which shows a more uniform and widespread distribution, makes the 100 hPa level a more relevant level to study the upper troposphere anticyclones.

The mean latitudinal location of the subtropical anticyclone from April to October indicates that in all levels the ridgeline exist in its lowermost latitude in April. During May it gradually shifts to higher latitude and reaches to its highest latitude in August. Then during September and October it shifted to lower latitudes again. The smallest zonal extension of anticyclonic circulation is at the 1000 hPa level and its largest zonal extension is at the 500 hPa level which amounts to about 40° (20–60 °W) and 180° (60 °W–120 °E), respectively. The maximum monthly variation in the latitude of the ridgeline is seen at 500, 200, and 100 hPa from June to July which goes even up to 10 degrees at some longitudes (Figure 7).

The above mentioned points about the spatial pattern of summer subtropical anticyclone centres, indicates that the mechanism and nature of the formation of subtropical anticyclones during the boreal summer must vary spatially. Location of the maximum frequency of summer subtropical anticyclone centres over the high mountainous regions in the middle and upper troposphere reveals the role of elevated heat sources in the formation and maintenance of anticyclones over Asia and Africa. Our finding confirms the previous results obtained from the summer monsoon circulation studies. It emphasizes the role of the thermal forcing of Tibetan plateau on the temporal and spatial evolution of South Asian High. On the other hand, it opens a new view for studying the role of high mountains in the formation and maintenance of summer subtropical anticyclones over southeast Asia and northwest Africa.

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