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Spatiotemporal Variations of Total Cloud Cover and Cloud Optical Thickness in Iran

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Abstract
A knowledge of cloud properties and spatiotemporal variations of clouds is especially crucial to understand the radiative forcing of climate. This research aims to study cloudiness in Iran using the most recent satellite data, powerful databases, and regional and seasonal analyses. In this study, three data series were used for the spatiotemporal variations of cloudiness in the country: A) Cloudiness data of 42 synoptic stations in the country during the statistical period from 1970 to 2005, B) Cloud Optical Thickness (COT) of Terra and Aqua MODIS sensors for 2003-2015, and C) Total Cloud Cover (TCC) of ECMWF Database, ERA-Interim version, for 1979-2015. The values obtained in the country were located via the kriging geostatistical method by RMSE. The results showed that the highest TCC occurs during the winter months. At this time of the year, the cloud cover is reduced from North to South and from West to East. Besides, COT showed that in the cold months of the year, the highest COT is observed in January and the lowest in March. The west and central Zagros highlands have the highest COT. Incorporating COT and TCC results showed that the two factors of height and approximation and access to moisture sources contribute significantly to the regional differences of cloudiness in Iran.

Keywords: COT, TCC, ECMWF Database, MODIS sensor, Iran.

1. Introduction
Clouds are special climatic phenomena that occur due to the effect of dynamic and thermodynamic changes in the general circulation of the atmosphere and affects the earth-atmosphere system in two ways: 1) It changes the earth radiant energy budget (Wild et al., 2004) by absorbing, dispersing, and reflecting solar radiation; and 2) It affects the hydrologic cycle by generating precipitation in various forms (Eftekhari, 2013). Understanding the physical properties of clouds, which are usually divided into two categories of micro-physical quantities (e.g., the effective radius of cloud droplets) and macro-physical quantities (e.g., cloud thickness), is particularly important (Holz et al., 2015) because these properties are closely related to short-term and long-term climate change in different parts of the earth.

Clouds cover about 60% of the Earth’s surface (You et al., 2014), and always have a significant effect on climatic changes by exerting direct effect on the amount of precipitation received by the area, the reflection of solar radiation short-wave, and the return of the wavelength exiting from the earth surface (IPCC, 2007). Similar to a blanket, the clouds also confine the greenhouse gases such as water vapor and carbon dioxide, which increase the tendency of the ground surface to warm up and can potentially lead to increased or decreased CO_2 effects in the atmosphere (Pincus et al., 2012). Thus, the reflection of solar radiation incoming by clouds results in shortened daylight length, reduced temperature and evapotranspiration, and finally the shortage of energy required for plants (Ackerman et al., 1998).

At present, there are many uncertainties about the effects of cloudiness on climate systems and their changes, such as height, thickness, horizontal range and diversity, water content, phase (liquid or ice), droplet size, and the type of cloud crystal (Meyer and Platnick, 2010). Moreover, the geographic location of the clouds, the reflection and temperature of different levels of the clouds, and the time of their formation are also important issues in the field of cloud studies, which have so far been neglected (Warren et al., 2007; Sanchez-Lorenzo et al., 2012).

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Cloud Optical Thickness (COT) is a key parameter for describing the optical properties of clouds and plays a significant role in evaluating the radiation induction (Zeng et al., 2012). Some studies with General Circulation Models (GCMs) have shown that COT variations have led to negative radiation feedback, which have in turn also contributed significantly to climatic warmness (Mitchell, 1989). However, some researchers have discussed the positive feedback of COT (Chang and Coakley, 2007). COT is a term with the approach of solar reflection from a non-absorbable water group at observable wavelengths, assumed that the reflection is one-to-one and non-linear (Zeng et al., 2012).

Studying the interannual changes and cloud trends is an important part of cloud studies in the global and regional scales. Platnick et al. (2003) evaluated the MODIS Cloud Products using various algorithms with the samples of Modis Terra and examined the results obtained from different spatial separations with different algorithms for the South Coast of the United States.

Total Cloud Cover (TCC) and its trend in the United States have shown that this measure has a decreasing trend in the country over the 1976-2004 period (Dai et al., 2006). The same measure has not significantly changed in Australia during the statistical period of 1976-2004 (Jovanovic et al., 2011). The spatiotemporal analysis of the amount of cloud cover in Russia for the period of 1991-2010 (Chernokulsky et al., 2011) has revealed that this measure has not shown a significant trend in this country. By comparing the NCEP/NCAR and ERA-40 bases for TCC on the Tibetan plateau, You et al. (2014) concluded that the amount of TCC decreases from the southeast to the northwest of the Tibetan plateau, which has been consistent with atmospheric humidity patterns. The authors also concluded that the amount of cloud cover has decreased in about 65% of stations. The assessment of cloud cover and its daily and seasonal changes on the Hawaiian Island using the data of Modis Terre and Aqua is a research conducted by Barnes et al. (2016). While evaluating the height of the cloud base in different regions of Hawaii, the authors concluded that the abundance of clouds have decreased by height and obtained a minimum amount of cloud in the months of December to January.

The importance of studying the clouds is essential because they are at the top of the hydrologic cycle, and any variation in them is the beginning of many changes in the climate system. In this paper review of available resources are based on the methodology. Research projects in Iran can be sorted into two general categories: 1) The studies that have evaluated cloudiness based on the data of weather stations; 2) Those studies of cloudiness that based on reanalysis and satellite data.

Among studies that have evaluated cloudiness based on climatic data is Rasouli et al. (2013). Using monthly information from 90 stations across the country, these authors concluded that the cloud cover in Iran was divided into five distinct regions, including the southern coastal zone of the Caspian Sea, Azarbaijan and Alborz, the western Zagros region, the southern slopes of Alborz, the southwest and north of the central desert, and the southern and central parts of the country. Ahmadi et al. (2018) evaluated the annual and seasonal spatial patterns and changes of cloudiness in Iran using the data of cloudy days from 43 synoptic stations from 1970 to 2010. They concluded that the number of cloudy days has a decreasing pattern from north to south and from west to east of Iran and that there is a significant difference in the number of cloudy days over the country. They also showed that the changes in cloudy days in the country had a decreasing trend, and more than one half of the stations studied have significantly shown this decreasing trend.

A group of the evaluated resources studied the cloudiness based on the reanalysis and satellite data. Analyzing the spatial and temporal variations of cloud fraction according to geographic features in Iran is a research that was conducted by Ghasemifar et al. (2017). The data sources included data from MODIS on Terra and Aqua satellites for a 15-year time-span, data from 120 weather stations and ERA-Interim reanalysis as well as geographic data (i.e., width, height, and vegetation cover). The results of their research indicate that the maximum standard deviation is in the fall for both satellite observations. Besides, the data analysis of ERA-Interim and satellites showed that non-significant trends are found in most months. Their results also showed that the cloud fraction is increased proportional to the increase in latitude. In another study, Ghasemifar et al. (2018) studied the spatiotemporal variations of cloudiness based on geographic features and remote sensing data in Iran. In this research, the same research data of Ghasemifar et al. (2017) was employed. The results of the monthly study of cloudiness in Iran showed a cloudiness over 65% for the cold months, especially in February and January, and 7% to 25% in June to September.

Because of the high spatiotemporal variation of clouds, it is necessary to monitor this important phenomenon of the atmosphere in the country in an appropriate period and with a good spatial resolution because understanding the optical and microphysical properties of clouds provides the ground for new methods of precipitation forecast. The results of the study can also be useful for studies on energy, solar farms, agriculture, and other related fields.

2. Research Methods

In this study, the data were collected and processed as follows:

2-1. Number of cloudy days of synoptic stations of the country

First, the statistics associated with the phenomenon of cloudiness or cloudy days from 42 synoptic stations during 1970 to 2005 were prepared from the Meteorological Organization. The phenomenon of cloudiness or cloudy days is measured in the weather stations on the earth surface as 0-2.8 no-cloud days, 2-3.6 partial days and 3-7.8 cloudy days. In this study, the measures of 3-7.8 were used.

2-2. COT based on the output of Terra and Aqua MODIS

In this study, Terra and Aqua MODIS cloud masks (Frey et al., 2008) known as the products of MYD08_D3 v6 and MOD08_D3 v6 (Ackerman, 2015) have been used. Both MODIS sensors (Terra and Aqua) scan the effects in a cross-track by using a radiometer near the polar SSO (Sun Synchronous Orbit) at the height of 705 km (Platnick et al., 2003). These two sensors have a 16-day cycle, but the wide scanning MODIS band (2300 km) allows to have a global cover nearly twice a day (once during the day and once during the night). The MODIS Cloud Cover Mask depicts the cloud cover with precision over one kilometer (Ackerman et al., 2008). COT is defined by measuring the damping of light passing through the atmosphere considering the dispersion and absorption by cloud droplets. The optical depth or COT (τ) has been described as the integrated Extinction Coefficient over a vertical column in a cross-section. A full description of COT relations and algorithms is presented by King et al. (1992, 2006). As stated, in order for the spatiotemporal variation of COT, the products of MYD08_D3 v6 (MODIS Aqua) and MOD08_D3 v6 (MODIS Terra) were taken from MODIS base in the daily time range from 01/01/2003 to 31/12/2015 AD with spatial resolution of 1 × 1 ° arc for Iran. After receiving and decoding data in Matlab, an array with the dimensions of 155×5475 was obtained (Figure 1a). In this array, 155 is representative of 155 cells of 1 × 1 ° arc of MODIS and 5475 is representatives of the days. In the next step, the array is presented as monthly that its dimensions are reduced to 155x125. The full information of COT considered in this paper is presented in Table 1.

Table 1. COT based on Terra and Aqua MODIS outputs.

Parameter retrieved	Researcher	Spectra bands used by MODIS	Spatial resolution	MODIS sub input	Non-MOSID sub input
COT (τ_c), effective particle radius, flow of water flowing through the cloud	King et al. (2003)	VIS, NIR, SWIR, MWIR (Bands 1, 2, 5, 6, 7, 20)	1	MOD35, MOD06 (ρ_c, T_c), Surface albedo and ecosystem	Water and cloud cover mask; model of T and p absorption; temperature of water surface

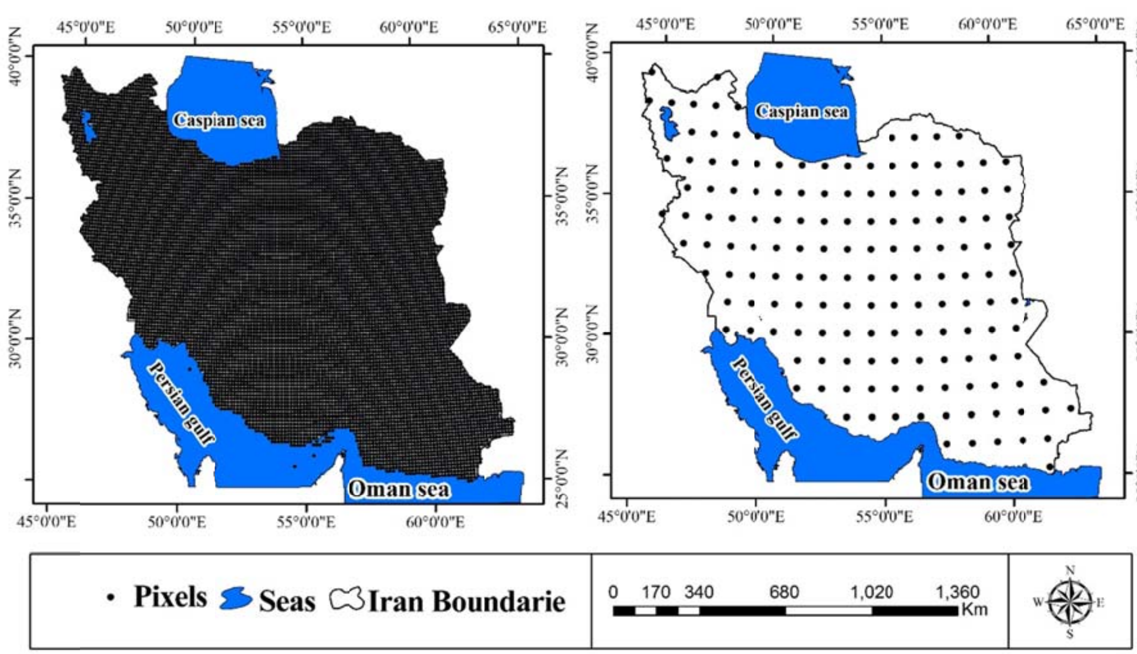
2-3. TCC based on the data of ECMWF-ERA-Interim

ECMWF- ERA-Interim is an independent international center formed by the membership of various countries globally. The analysis data of ECMWF center is the result of a complex interaction between the available data and the results of atmospheric patterns, and are presented as a dataset. The latest product presented by this database is the ERA-Interim version. It is an improved edited version and enhancement of some features of ERA-40 version of the same organization (Darand and Zand Karimi, 2015). In this research, TCC of this database for the period of 1979 to 2015 was loaded on a monthly basis with a spatial resolution of 0.125× 0.125 ° arc. Similar to the COT data, the TCC data were decoded in Matlab whereby an array with dimensions of 432 × 9966 was obtained (432 is the number of months studied and 9966 is the number of cells of 0.125 × 0.125 ° arc). In the next step, the monthly average for the long term is obtained, and the array dimensions are reduced to 9966 × 12 (Figure 1b). The total cloud cover based on the ECMWF data is presented as a dimensionless scale that varies from 0 to 1 (Jakob, 1999). The zero value is somewhat lacking in cloud cover and 1 is the full amount of cloudiness, which is 100% cover or full cloudiness condition.

2-4. Preparing the cloud cover maps

According to the regional analysis of the TCC and COT in Iran, the geostatistical method of kriging in ARCGIS software with a root mean square error (RMSE) of 2.22 was used.

The evaluation of cloudiness days in Iran based on the selected synoptic stations showed that in Iran, the maximum cloudiness days with 167.3 days have occurred in the Rasht synoptic station and the minimum cloudy days with 14.8 days have occurred in the Chabahar synoptic station (Table 2). The average number of cloudy days in Iran is 54.15 days. Seasonally, the maximum cloudy or cloudiness days are in winter with 7.7 days and the minimum cloudy or cloudiness days are in the summer with 1.3 days. Cloudiness in fall is more than spring. Among the seasons, the highest skewness is observed in summer and the lowest in winter. In fact, during the dry seasons, only parts of the Caspian region and the south and southeast of the country in the coastal areas experience the cloudy days.



(a) (b)

Figure 1. (a) 0.125 × 0.125° arc-cells of TCC of ECMWF ERA-Interim base.; (b) 1 × 1° arc-cells - of COT of aqua and Terra MODIS for Iran.

Table 2. The number of cloudy days of the selected synoptic stations in the country (average annual sum of 1970-2005).

Station	Cloudy days per year	Station	Cloudy days per year	Station	Cloudy days per year	Station	Cloudy days per year
Abadan	34.5	Chabahar	14.8	Kermanshah	60.4	Shiraz	47.5
Ahwaz	36.3	Dezful	49.9	Khorramabad	52.4	Tabas	36.2
Anzali	162.3	Isfahan	33.9	Mashhad	61.7	Tabriz	76.9
Arak	34.5	Fasa	26.9	Oroomieh	62.2	Tehran	51.2
Ardabil	53	Qazvin	69.3	Ramsar	159.2	Torbat-e Heydarieh	35.6
Babolsar	120.2	Gorgan	116.2	Rasht	167.3	Yazd	35
Bam	16.8	Hamedan Nozheh	50.7	Sabzevar	50.8	Zabol	20.3
Bandar Abbas	17.8	Iranshahr	18.8	Saqqez	57.5	Zahedan	27.2
Bandar Lengeh	16.4	Jask	17.2	Sanandaj	58.5	Zanjan	62.3
Birjand	29.7	Kashan	36.5	Semnan	31.5		
Bushehr	38.8	Kerman	36.8	Shahr-e Kord	36.8		

Finally, the data of the two bases was called in ArcGis 10.2 software setting, and the results were presented as TCC and COT maps (in microns). An evaluation of different interpolation methods has shown that the kriging method with an RMSE value of 2.22 has the best function compared to other proposed methods. Accordingly, the same method is utilized in this study.

3. Results and Discussion

3-1. Cloud cover distribution in winter

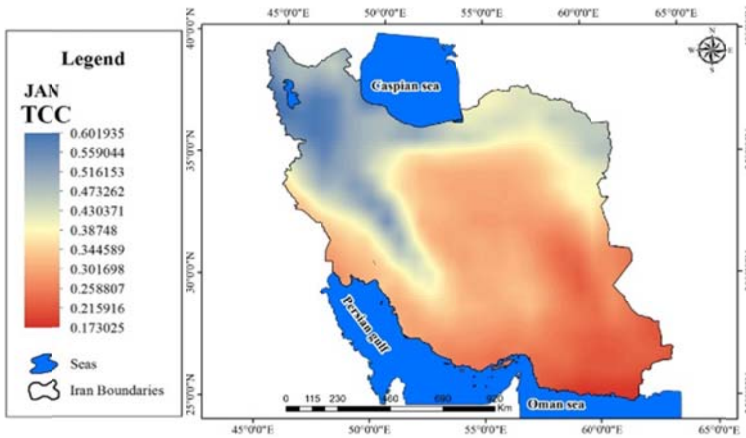
In January, cloud cover is at the highest level of 0.60 and at the lowest level of 0.17. In this month, the cloud cover follows an uneven trend; the highest cloud cover is located in the northwest and central Zagros Mountains (Figure 2a). In this month, the amount of cloud cover decreases from north to south and from west to east. The blocking role of uneven lands and the Zagros mountain range has caused central Iran to have the least amount of cloud cover.

In February, the cloud cover increases and, in fact, reaches its highest coverage in the country. In this month, the expansion of cloud cover is observed to be 0.62 at the highest level. Given the peak of the coldness and the penetration and spread of precipitation and wet systems in a systemic mechanism in February, cloudiness rises in this month. During this month, the areas covered by clouds increase and cloud coverage reaches its highest level in the country. Almost all the mountainous areas on the uneven axis are covered by clouds. On the other hand, the East and South and Central regions of the country have the lowest cloud cover because of the lack of humidity and being surrounded by the north and west mountainous areas (Figure 2b).

As revealed by Figures 2 to 4, the topographically forced flows have the largest contribution in determining the diurnal cycle of cloud activity over the arid/semi-arid regions in Iran.

In March, the extent of area with total cloud cover is gradually reduced. In fact, along with the gradual increase in the temperature of the earth surface and the penetration of warm flows into the area, the total cloud cover gradually shifts to higher latitudes of the country under the effect of the latitude factor. In this month, the highest level of cloud cover is observed at 0.58 in the mountainous areas adjacent to the Caspian Sea. During this month, the central Iran and southern areas of the country are among the poorest areas in terms of cloud cover (Figure 2c).

In the winter months, the highest total cloud cover occurs in the country. This time of the year is coincided with the precipitating system in the country and amount of cloud cover is increased. At this time of the year, the amount of cloud cover is decreased from the north to the south and from the west to the east. Cloud cover follows the factor of density of uneven lands and their process, so that the east and south and Central regions of the country have the lowest cloud cover because of being surrounded by the northern and western uneven lands.



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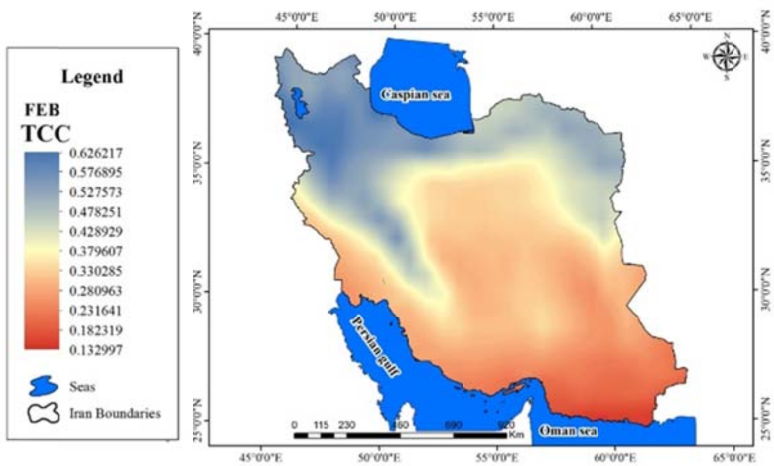

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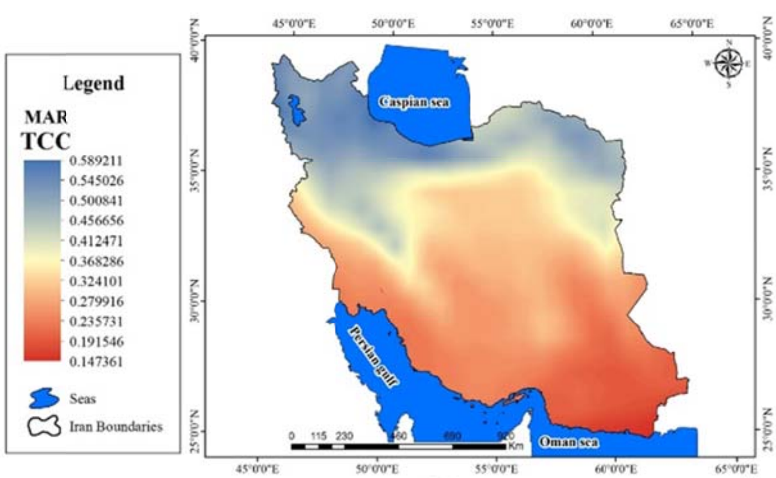
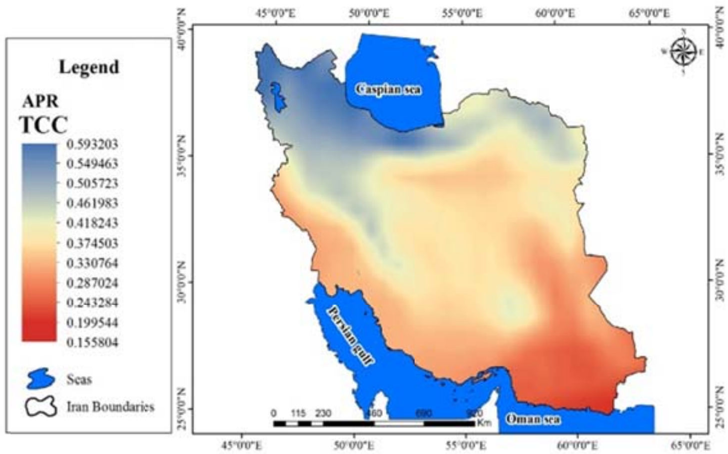


(c)

Figure 2. TCC (Total cloud cover): (a) January; (b) February; (c) March.

3-2. Distribution of cloud cover in spring

In April, with the arrival of the warm half of the year, the cloud cover gradually decreases. Cloud cover reaches 0.59 as the highest level in this month of the year. The main areas under TCC are the northern parts of the country, especially margins of the Caspian Sea and the northwestern region of the country (Figure 3a).



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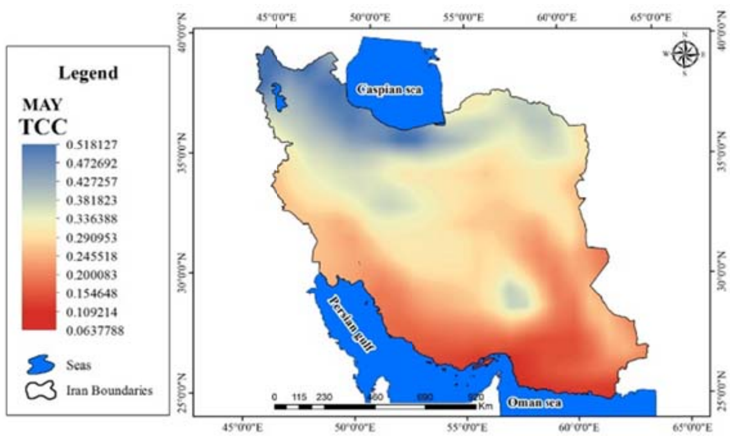

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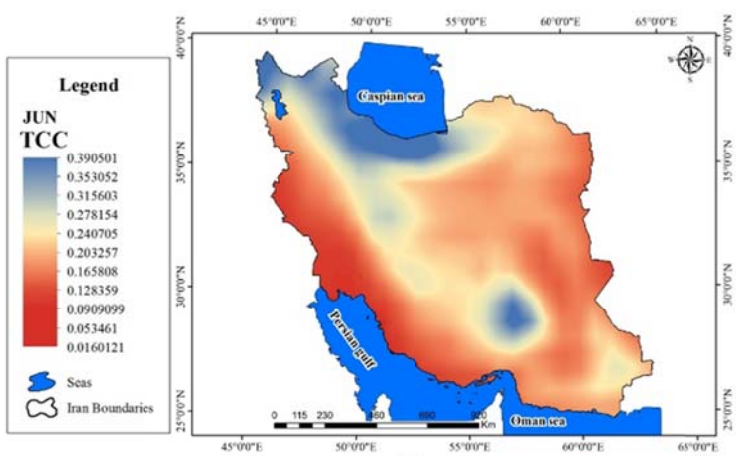


(c)

Figure 3. TCC a) April; b) May c) June.

In May, only high latitudes and margins of the Caspian Sea account for up to 51% of the cloud cover (Figure 3b). Cloud cover reaches 0.05 in the central and southern regions. In this month of the year, there is an approximately cloudless and clear sky in the southern and central parts of the country. With the gradual heating of the air temperature, the cloud cover gets limited to higher latitudes. At this time of the year, in Khorasan and northwest regions, the cloud cover results in sudden spring precipitation due to the convection over the slopes.

In June, cloud cover is observed only in areas of high latitudes of Azerbaijan and in Mazandaran and Gilan. In this month, the cloud cover reaches 0.39 at the highest level. In the south, Kerman area have cloud cover due to the influence of the monsoon in the southeast of the country. In other parts of the country, no cloud cover is observed. This month is the beginning of a totally dry period with clear sky and full radiation in the country (Figure 3c).

In spring, as the air temperature gradually increases, the amount of cloud cover decreases. In the months of April and May, due to the role of temperature and daily irradiation and night cooling, the phenomenon of convection occurs over slopes, and the spring rains fall in the northwest and northeast regions. In June, the southern region is gradually affected by the monsoon systems, and the cloud cover occurs in Kerman area.

3-3. Distribution of cloud cover in summer

In the first month of summer, as the temperature rises, the cloud cover reaches 0.38 at the highest level of the Caspian Sea. Other regions of Iran are not particularly covered. Only highlands in the central Zagros and Kerman area have cloud cover due to the influence of monsoon and southeastern systems (Figure 4a).

August is similar to July in terms of cloud cover, with the exception that in August, the size of the area covered by clouds reduces, and the relatively moderate cloud cover is observed in most of the regions of the Caspian Sea and high altitudes of the central Zagros and Kerman (Figure 4b).

In September, with the exception of the Caspian region, the entire country is without cloud cover and has a clear and sunny sky. When the southern and southeast systems retreat, the southern regions and southwest areas have no cloud cover (Figure 4c). In the summer, cloudiness in the lower and upper latitudes is more than other areas, which respectively show the effect of Monsoon and Beach Convection for these areas.

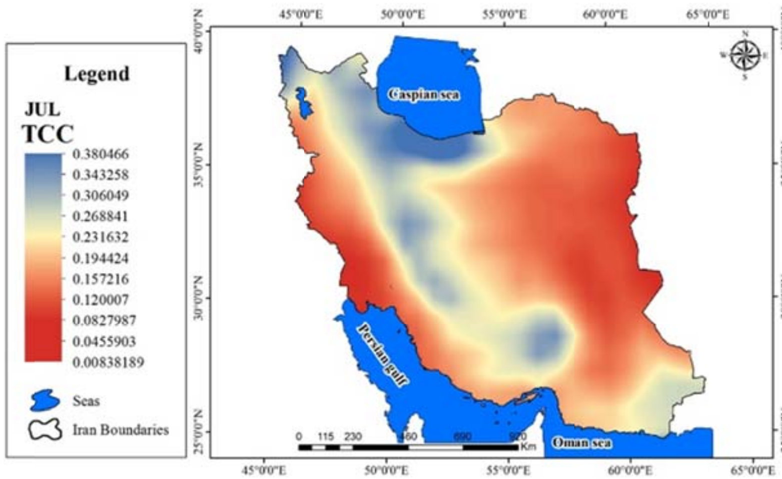
3-4. Distribution of cloud cover in fall

In October, with a seasonal transition and a relative decrease in the temperature from the northern part of the country, the cloud cover gradually increases from the Northwest area. Cloud cover reaches 0.64 in northern and northwest areas. Other areas of the country are without cloud cover and with the reduction of the air temperature, the southern regions are gradually accompanied by cloud cover (Figure 5a).

In November, cloud cover reaches 0.61. In this area, there is cloud cover gradually from the northwest to the lower latitudes to the areas of the northern Zagros and western slopes of Zagros (Figure 5b).

In December, an increase in cloud cover is observed, such that the highest level reaches 0.56. During this month, the west, north, and northwest regions have sufficient cloud cover. In northeast regions, a relatively moderate cloud cover is also gradually formed (Figure 5c).

The monthly results show that the spatial distribution of cloudiness in Iran is a function of altitude from the sea level and latitude, distance and proximity to water bodies. Due to its geographic location, Iran is considered an almost cloudless country. Except for the Caspian region, the cloud cover of the country is affected by rain-fed systems during the cold season and local convection. Therefore, the amount of cloud cover is reduced from the north to the south and from the west to the east. The regions with the highest precipitation are among the regions with the highest cloud cover. The effect of atmospheric conditions and local sustainable factors provide the ground for cloud cover as a systemic mechanism.



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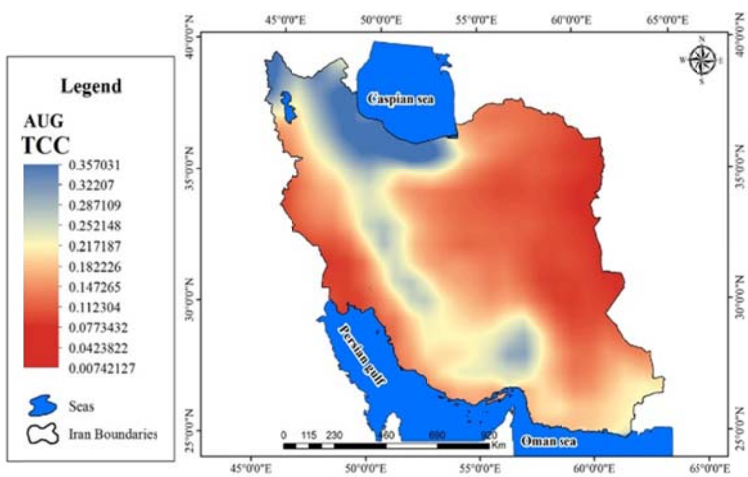

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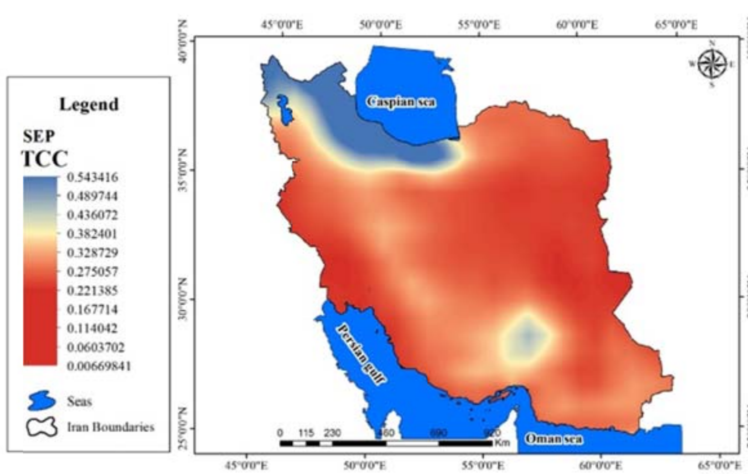

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Figure 4. TCC a) June; b) August; c) September.

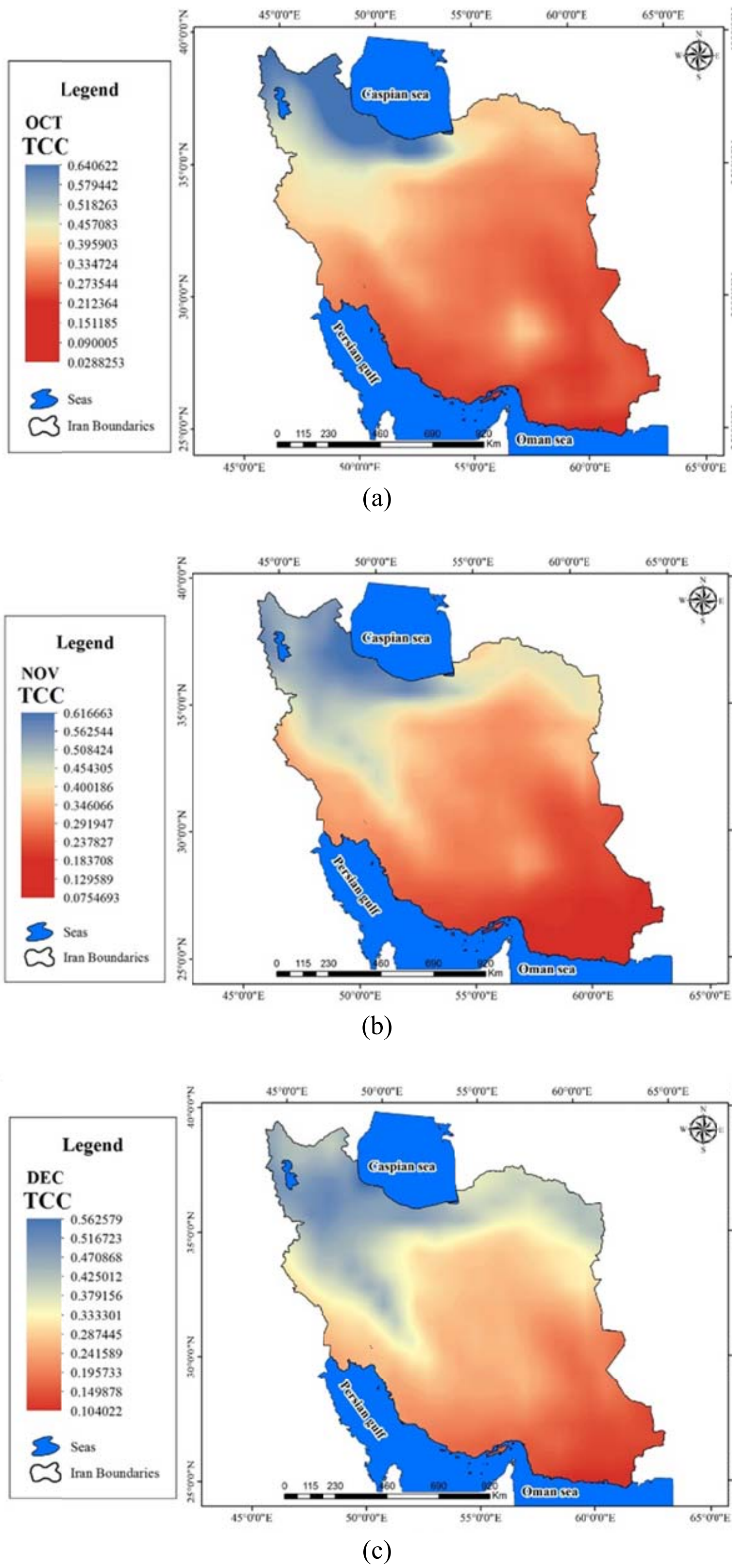


Figure 5. TCC: a) October; b) November; c) December.

Ghasemifar et al. (2018) found that the highest percentage of cloudiness ranging from 55% to 67% was observed in the months from December to January and the lowest percentage (7% to 25%) was observable in June, July and September, which is consistent with the results of this study.

Sato et al. (2007) explained the process of cloud formation in mountainous areas in the transitional seasons (spring and autumn), which is consistent with the results of the present study. Because of solar radiation, the atmosphere above the slope is heated by the sensible heat flux from the surface, which causes the upslope wind in the lower layer. The convergences of the upslope wind and the moisture form clouds near the mountaintop. Another explanation for cloud formations can be as follows. If the temperature in the middle troposphere is assumed almost the same between the atmospheres over the mountain and the surroundings, the clouds tend to appear more frequently over the mountains.

3-5. Cloud optical thickness (COT)

3-5-1. COT in the cold months of the year

In general, COT of the cloud cover shows a significant difference across the country in January. As shown in Figure 6, the highest COT is up to 38 microns in the high Zagros region and the central and western parts of the country. At the same time, COT in the region adjacent to the Caspian Sea is relatively less than the high Zagros regions and the west of the country. In terms of spatial distribution in the country, Zagros highland on the west and southwest and adjacent to the Caspian Sea has the highest COT, while the central and southern regions of the country have the lowest amount of COT per micron. From the north to the south and from the west to the east, the thickness decreases and becomes almost negligible. In fact, due to the increase in cloud cover in winter, COT also increases (Figure 6a).

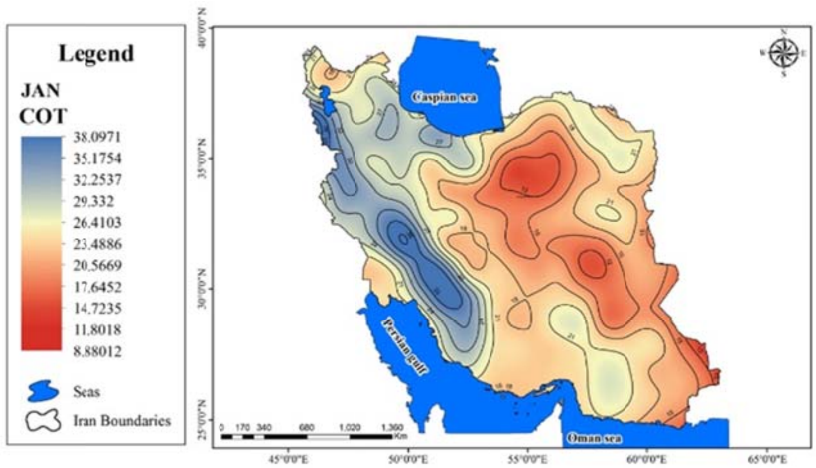
In February, in proportion to the expansion of the cloud cover, COT also increases in regions where the cloud cover is more complete. The highest COT is observed in the west region, the southwest region, and the northern region (Figure 6b). In this month, COT reaches 30 microns in the central Zagros highlands, Kurdistan, and southwestern Azerbaijan. The lowest COT is observed in the southern and central regions of Iran, especially the desert areas, which are considered as the areas with the lowest cloud. In March, COT in the cloud cover is decreased, but, in contrast, the extent of the COT is greater than other cold months of the year. In this month, COT is still more observable in the uneven areas of the West, Northwest, and North of the country, where COT reaches 25 microns in these areas at its highest level. In these areas, due to the increase in temperature compared to other cold months of the year, COT is found less (Figure 6c). During this month, given the reduced cloud cover, COT is also less observed. The lowest level is 9 microns in the southern and southeastern regions.

In general, in the cold months, the highest and lowest COT is observed in January and March, respectively. From the beginning of the winter to the end, COT of the cloud cover is reduced but its spatial extent increases. The results showed that the highlands of central Zagros and western parts of the country have the highest COT. This shows that these regions are cloudier during the cold season of the year and that they become cloudier and COT increases significantly in proportion to the influence of cloud-creating systems.

3-5-2. COT in the spring months

In April, the COT status changes. In this month, the spatial extent decreases by high COT so that in the southern and central regions of Iran, COT is also found to be 2 microns (Figure 7a). In fact, with the gradual increase in the temperature, the amount of cloudiness in the arid regions of the country is reduced, and as a result, COT in the sky of these areas is also greatly reduced. During this month, the Zagros and Albert heights have up to 26 microns of cloudiness, and their spatial range is gradually decreased and limited to higher latitudes.

The upslope wind tends to transport the lower layer moisture as it converges near the mountain top [Kimura and Kuwagata, 1995]. The advected moisture is further transported by the ambient wind causing a diurnal cycle of convective instability around the mountain, which, consequently, forces a pronounced diurnal cycle of the cloud activity and the precipitation systems (Sato and Kimura, 2005).



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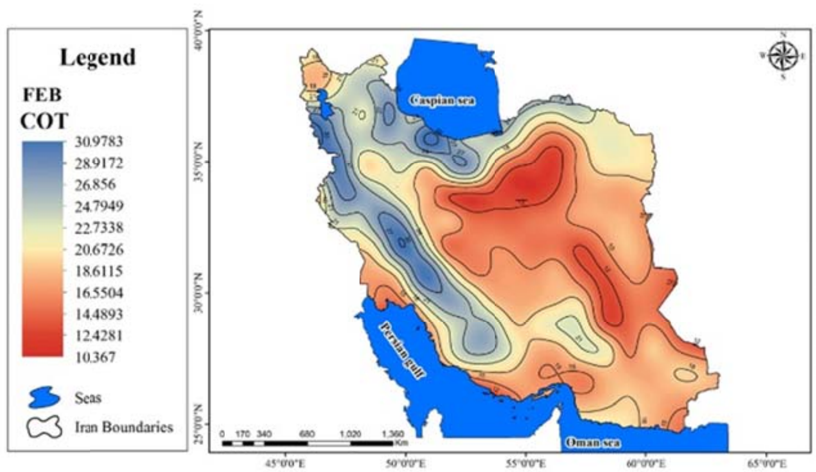

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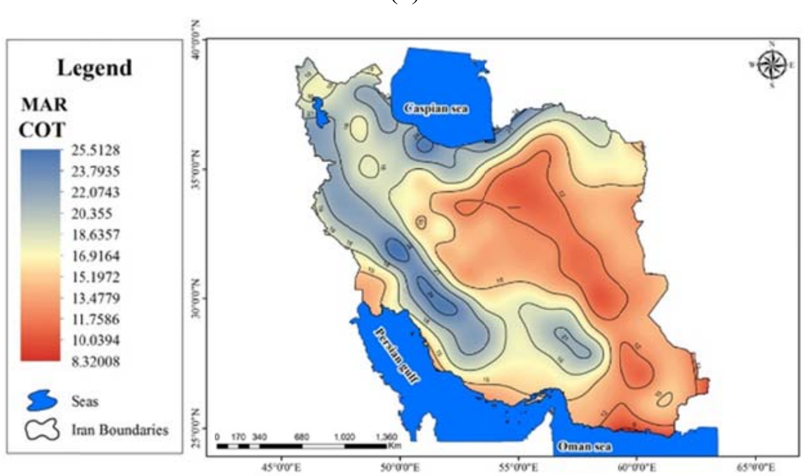


(c)

Figure 6. COT: A); January; B) February; C) March.

In May (Figure 7b), the appearance of COT changes significantly, so that COT at the highest level is significantly higher than in April, and the spatial area of COT is limited to the highlands of Kerman and the east of the country and the northern and northwest regions. Therefore, the highlands of Sistan and Baluchestan and South Khorasan have a COT up to 26 and 27 microns. In this month, only high altitudes show high COT.

In June, COT is observed as more dispersed up to 38 microns at higher altitudes. This amount of COT is at the highest level during the spring months. The highest COT is observed in the central Alborz and the northern region of the country, and the lowest COT is observed up to 2 microns in central and desert areas and the southern region. During this month, considering the increase in the temperature of the earth surface and the air temperature in the desert, only areas with higher latitudes and higher altitudes with cloudiness have higher COT. The high altitude of Central Zagros and other scattered heights in the country have also COT (Figure 7c). In the southeastern parts of the country, due to the cloudiness occurring under the effect of Monsoon, COT is also relatively high in these areas.

In the spring months, the optical depth and thickness gradually decrease in April, and there are greater spatial area and extent across the country during this month. In May, the eastern and southeastern highlands also have higher levels of cloudiness. In June, the depth of optical thickness is gradually increased, and the southeastern regions also have a significant depth of thickness.

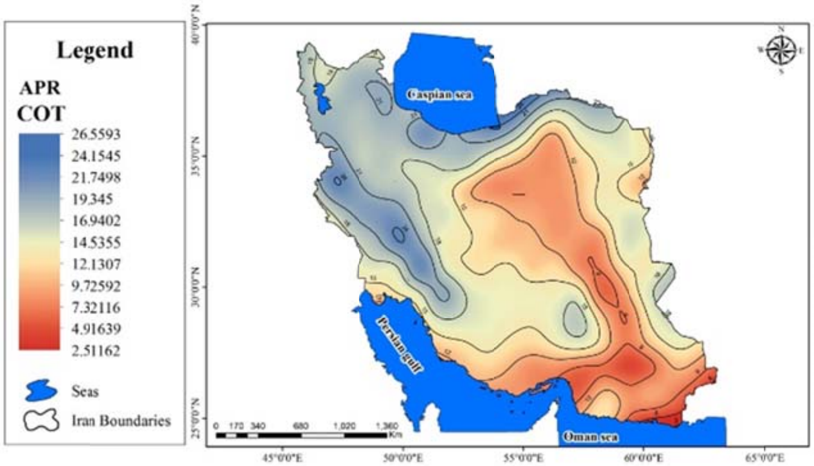
3-5-3. COT in the summer months

In July, COT is gradually decreased in microns. During this month, the highest depth of thickness is 34 microns in the clouded areas of the high latitudes in the north and northwest of the country. According to the cloudiness status in this month of the year, which is located on the uneven land axis, COT is more observed in the north and northwest areas. The central and southern regions of the country have the lowest COT.

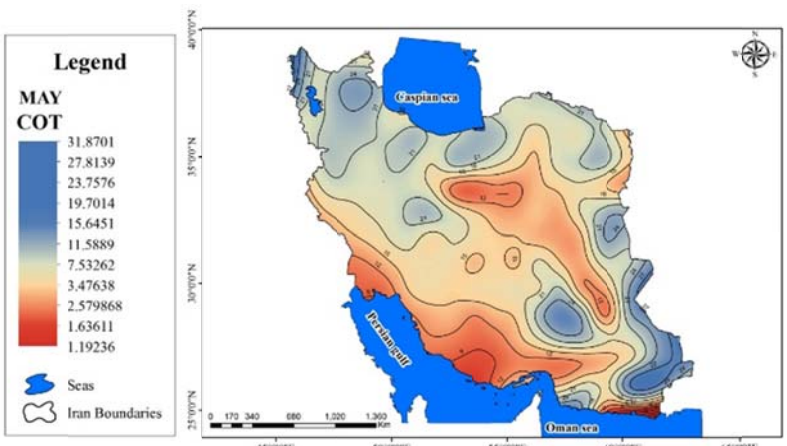
COT in August is similar to that of July. During this month, COT in the southern regions of Hormozgan and south of Kerman varies between 21 and 24 microns depending on the cloud cover formed in these areas. During this month, due to the increase in the earth surface and air temperatures, the cloud cover is limited to the very high latitudes of the country and the adjacent Caspian regions; thus, the COT is also higher in those areas with cloud cover (Figure 8).

In September, the depth of optical thickness decreases, and the COT is limitedly observed in only two zones in the northwest and the south of the country with cloud cover. COT is observed more in the southern regions than in the northern regions. Although the extent of cloud cover in the south of the country is not vast, COT in these areas is higher than in the northern latitudes of the country (Figure 8). The south of the country is affected by the Persian Gulf moisture resources and the Sudanese masses, as well as the Indian Ocean for some periods of the year.

During the summer months, COT is found to be up to 34 microns. In May, July, and August, COT is higher than in September. In that season, in the southern regions of the country, COT is also limitedly observed in proportion to the cloud cover that is formed. In September, the southern regions have higher COT, especially the south of Kerman, Hormozgan, and Sistan and Baluchestan. The increased cloudiness in the south and southeast of Iran during the warm period of the year is associated with the Monsoon system in July to September, as confirmed by Ghasemifar et al. (2018) and discussed by Yadav (2016).



(a)



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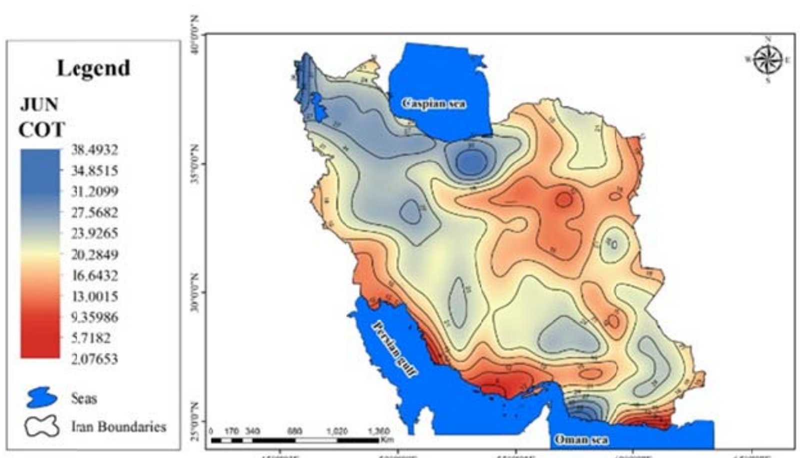

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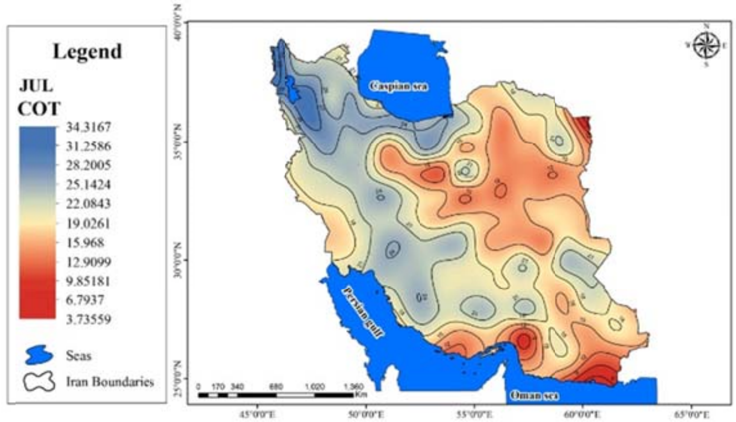
Figure 7. COT: a) April; b) May c) June.



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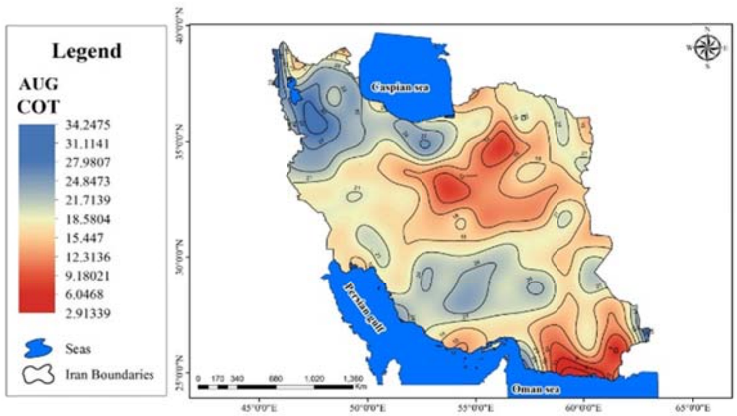

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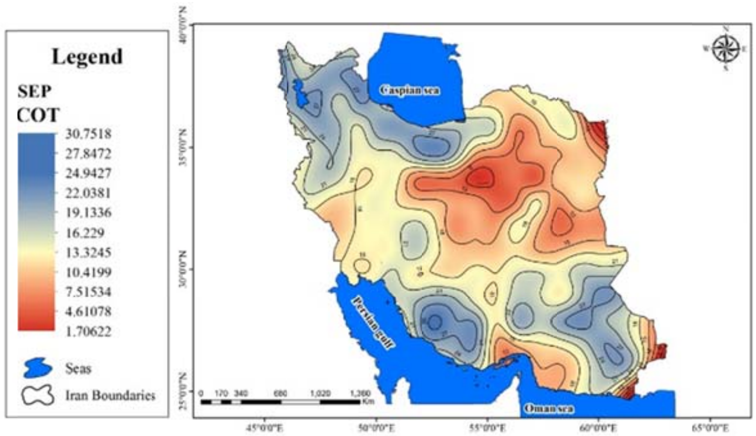


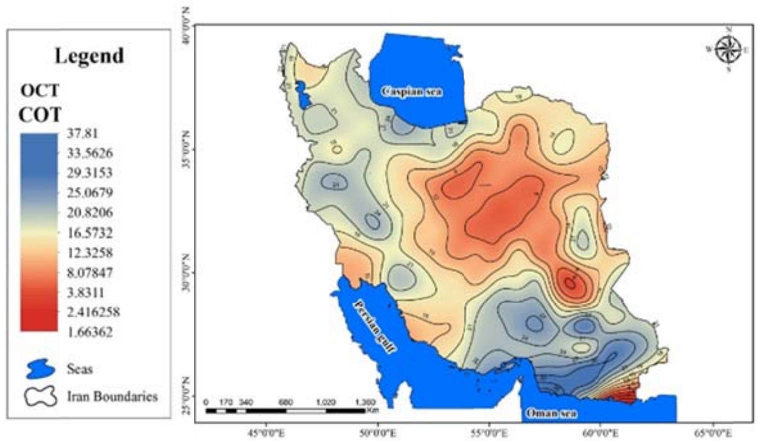
(c)

Figure 8. COT; (a) July; (b) August; (c) September.

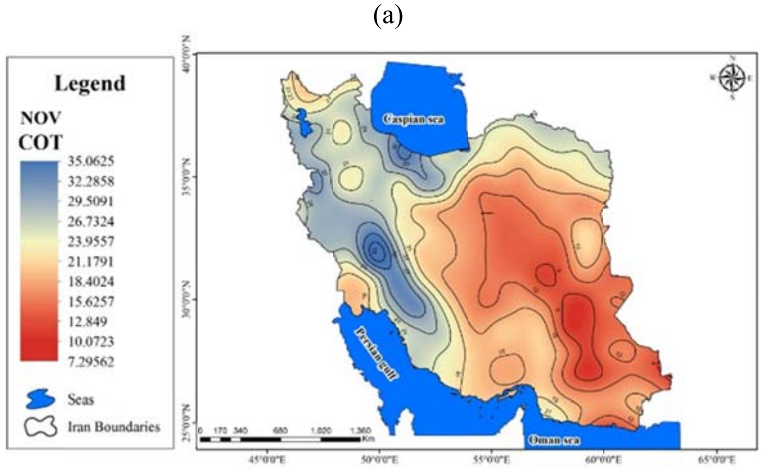
3-5-4. COT in the fall months

In October, COT increases and reaches 37 microns in the cloudiest areas. During this month, COT in the southern and southeastern parts of the country is higher than in other parts. In Hormozgan, southern Kerman, and Sistan and Baluchestan, COT is observed up to 30 microns. The depth of COT in the southeast of the country is higher than in the northern regions of the country (Figure 9-a).

In November, along with the gradual cooling of the temperature, the status and arrangement of COT gradually change consistent with the cloud cover. In this month, the depth of the thickness is reduced, and the optical thickness distribution is limited to the mountainous areas and the axis of uneven lands commensurate with the latitude and elevation parameters (Figure 9b). In the western parts of the Caspian plain and in high Zagros areas, COT reaches 30 microns. In these regions of the country, due to the topographic conditions, the cloudiness is higher and, correspondingly, COT is observed at a higher level. The lowest COT is still observed in the central, desert, and southern regions of the country.



(a)



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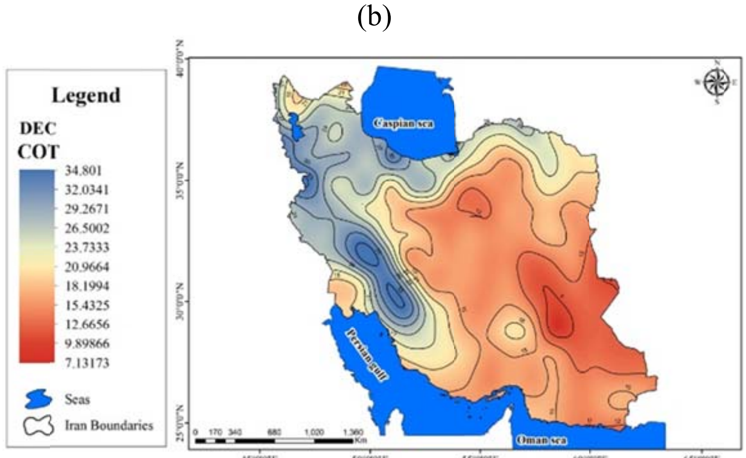

(c)

Figure 9. COT: a) October; b) November; c) December.

In December, considering the cloud cover in the mountainous regions in the west, southwest and the north, the highest COT up to 30 microns is observed in high mountainous regions. In this month, COT is decreased compared to November. However, the arrangement of thicknesses of cloudiness is more colorful in Alborz and Zagros mountainous regions (Figure 9c). In other regions of the country, COT is negligible and insignificant.

In the fall months, COT is more observed in October compared to the other months, with the difference that the arrangement of the optical thickness in this month is less dispersed and more variable than in the other months. In November and December, COT has a greater depth in proportion to the decrease in the temperature and the increase in cloudiness.

Analysis of latitudinal forcing on cloud fraction showed that an increase in cloud fraction is accompanied by the increase in latitude; this pattern is true only up to 31.5°N in summer. The reverse pattern is related to the Asian Monsoon system over Iran in low latitudes. Topographic forcing in this mountainous area often leads to orographic convection in the elevations of 500–1500 m during spring and fall and to coastal convection during summer. Ghasemifar et al. (2018) have identified the diversity of air masses as the main contributor to variability of the cloud content in Iran. By studying the analysis of spatiotemporal variations of the cloud fraction based on geographic characteristics across Iran, Ghasemifar et al. (2017) concluded that comparing the results obtained from the mentioned research with the regional evaluations of COT and TCC of this study is highly consistent and, in other words, confirms the results obtained in this study.

In order to better compare the temporal variations of TCC and COT values in Iran, the diagram of each of the seasons was drawn for the two values studied (Figure 10). In the preparation of diagrams, the average of the whole country was used as a time series (data comparison began since 2003, when the satellite data was available). The results of this diagram shows that the changes in TCC and COT are hand in hand with each other; in other words, this diagram depicts clearly the behavior of TCC and COT where increase in one corresponds with rise in the other, as discussed earlier.

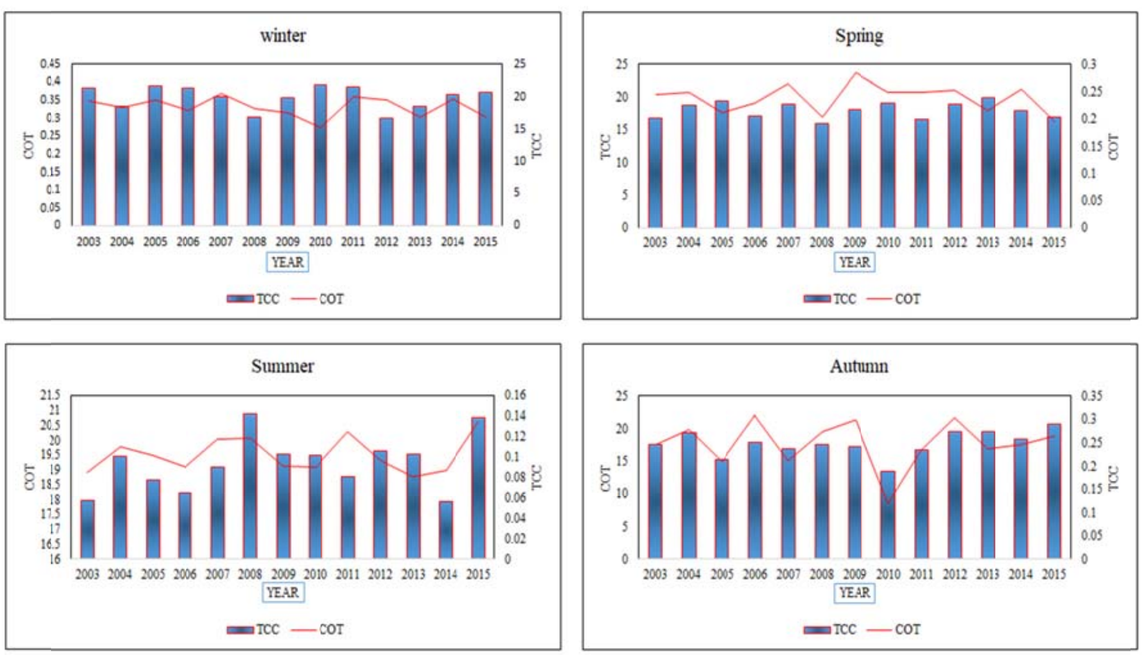

Figure 10. Seasonal/Temporal variation of total cloud cover and cloud optical thickness in Iran.

4. Conclusion

The results of this study showed that in the winter months, the highest total cloud cover occurs in the country. At this time of the year, the amount of cloud cover is decreased from the north to the south and from the west to the east. Cloud cover follows the factor of density of uneven lands and their process, such that the east, the south, and the central regions of the country have the lowest cloud cover because they are surrounded by the north and west uneven lands. Rasooli et al. (2013), who evaluated the cloudy days in Iran using station data, concluded that the central Iran has the lowest number of cloudy days in the country, which is consistent with the results of the present study.

In spring, along with the gradual increase in the air temperature, the cloud cover decreases. In the months of April and May, given the role of temperature, daylight, and night-time cooling, the cloud cover occurs in the northwest and northeast regions. In June, the southern region is gradually affected by the monsoon systems and the cloud cover occurs in Kerman areas. The regional evaluation of COT and TCC have shown that cloudiness in Iran has a substantial effect on the synoptic patterns of the incoming air masses and the direction of cyclone coming into the country because there are no significant moisture sources in the central areas of the country that can produce a significant cloud.

The monthly results of the cloud cover showed that in Iran, the spatial distribution is a function of altitude, latitude, and the distance to water bodies. Considering its geographical location, Iran is almost considered as a country without significant cloud cover, and except for the Caspian zone, the cloud cover of the country by the dynamic and thermodynamic mechanisms is affected by the precipitating systems during cold days and the local convection. Therefore, the cloud cover is reduced from the north to the south and from the west to the east.

Generally, in the cold months, the highest COT is observed in January and the lowest COT is observed in March. From the beginning of winter to its end, COT decreases, whilst its spatial range increases. The results showed that the central and west Zagros highlands have the highest COT because during the cold period of the year, low-pressure systems, and middle latitude waves and mesoscale atmospheric fronts of play decisive roles in increasing cloudiness, a finding that is consistent with the results obtained by Masoudian (2011). The Alborz zone and north west are affected by westerly winds on most days of the year, and since the westerly winds cross over the Mediterranean Sea and the sea also has sufficient moisture, it brings about considerable cloudiness for the area. The result obtained is consistent with the findings of Alijani's study (2006), who stated that the abundance of cloudy days over Alborz Mountains, Khorasan highlands, and northern Azerbaijan was 120 days. In the spring months, the optical thickness and depth gradually decrease from April, and a more spatial range is observed in this month in the country.

In June, the optical depth is gradually increased, and the southeast regions also have a considerable depth of optical thickness. In the summer months, COT is observed up to 34 microns. In May and August, the thickness is higher than that in September. Another important factor is the increase in thickness and cloud cover in southern Iran due to the influence of the Sudanese system, which sometimes extends to the central Iran and the east and the southeast of the country. This finding is consistent with the studies conducted by Mofidi and Zarrin (2005). In the fall months, optical thickness is higher in October than in other months, with the difference that the arrangement of the optical thickness of this month is less dispersed and more variable than in other months. In November and December, COT has a greater depth in proportion to the decrease in temperature and increase in cloudiness.

The results and findings of this study are important in terms of spatiotemporal distributions of TCC based on remote sensing knowledge. The results of this study are important for providing a better understanding of TCC per month as well as the depth of its optical thickness based on the MODIS sensor images. The results can also be important in managing water resources, agricultural management, navigation, and solar energy management.

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