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Investigating the Spatial Variations of Cloud Cover Properties Over Iraq

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Abstract: *Clouds are collections of water droplets, ice crystals, or combinations of the two, suspended in the atmosphere. This work aims to study the spatial monthly variations of cloud parameters such as cloud base height, cloud types of high, medium, and low, and total cloud cover over Iraq using European Centre for Medium-Range Weather Forecasts ERA5 data for the period 2010-2019. Findings show that maximum cloud base height occurred over southern Iraq in May and reached more than 6.5 km, while minimum cloud base height occurred over northern Iraq in January and reached less than 2.5 km. Higher high, medium, low and total cloud cover occurred in the northern region, reaching 0.35, 0.3, 0.45 and 0.6 respectively. Also, the results indicate that no cloud activities are occurring over all regions of Iraq from high, medium, and total clouds in the months of June-September, and low clouds in the months of May-October. The results of this paper can help policymakers to invest in continuous monitoring and research of cloud properties in improving forecasting accuracy, supporting water and energy management, strengthening climate resilience planning, and ultimately contributing to sustainable development.*
Keywords: *Microphysics of cloud, Cloud cover types, Cloud base height, Spatial analysis, Iraq*

INTRODUCTION

A cloud is a large visible collection of very small water droplets, ice crystals or a mixture of both, suspended in the Earth's atmosphere. Clouds can be thick or thin, large or small, and come in a seemingly endless variety of shapes (1). For a cloud to be visible, cloud particles must be present in a sufficiently high concentration. They form when moist, warm air rises, cools and condenses around small particles such as dust or salt. This descriptive definition has its origins in operational weather forecasting, where observers report the proportion of the sky covered by clouds. However, clouds play a vital role in the Earth's weather system by influencing precipitation and temperature, which play an important role in the balance between incoming and outgoing energy, known as the Earth's radiative budget, because they can reflect, absorb and radiate energy (2). The more variable related to clouds is cloud cover, which refers to the proportion of the sky covered by clouds when observed from a given location at a given time (3). A more precise definition of cloud cover is used when information is derived from satellite data, which nowadays provide a global picture of the total cloud cover. Satellites are essential tools for observing clouds from space and understanding clouds on a global scale. They provide detailed real-time information that helps scientists and meteorologists monitor cloud formation, movement, and structure. Cloud formation depends on several variables that mainly determine cloud type and control precipitation at a given location (4). Cloudiness is caused by the vertical movement of air, e.g., convection or forced ascent over higher terrain, or by the large-scale vertical movement associated with low-pressure systems or fronts (5) (6). Clouds form whenever and wherever there is more water in a given volume of the atmosphere than it can hold as vapour (7). The point at which the air can hold as much water vapour as it can without forming liquid water is called the saturation point. The amount of water vapour it can hold decreases as the air cools (8). The most effective cooling process in the atmosphere is buoyancy. As air rises, its pressure decreases, allowing it to expand and cool; with sufficient cooling, the air reaches saturation and small cloud droplets begin to form (9). The number and size of droplets depend on the degree to which the atmosphere is oversaturated with water vapour, and the number and properties of tiny particles called cloud condensation nuclei on which the water condenses (10). When enough droplets of at least a few tenths of a micron are formed, they become visible as a cloud (7).
The microphysical parameters and properties of the cloud are of interest to several researchers. Cecchinia et al. (11) investigated typical droplet size distributions for different types of precipitation systems and cloud condensation nuclei concentrations in southeastern Brazil using numerous instruments. By comparing the two retrieval methods, Li et al. (12) analyzed the global distribution and long-term

variability of cloud droplet number concentration-cloud effective radius retrieval from MODIS. In 2021, Using CloudSat/CALIPSO satellite data, Miao et al. (13) examined the observational basis of cloud microphysical properties over three selected regions in East Asia. In arid regions of central Asia, Zhao et al. (14) studied the temporal and spatial variation of cloud cover and found that total cloud cover was low in the south and high in the north. The frequency distribution of high and medium cloud cover was higher in the south and lower in the north. In 2023, Al-Zuhairi et al. (15) studied the to study the spatiotemporal variations of cloud properties (e.g., liquid and ice water content) over six selected cities of Iraq (Mosul, Khanaqin, Baghdad, Rutba, Kut, and Basra) at the upper pressure levels for the period (1981-2020) and it was found that ice water was present at higher altitudes, peaking at over 13 kg/kg above Mosul, and that liquid water extends from the surface to about 500 hPa for all cities. This result can be supported by the recent references carried out in Iraq using ERA5 data from the European Centre for Medium-Range Weather Forecasts (ECMWF) (16)(17), in which the cloud liquid water content had a significant difference in the behavior of CLWC across the different cities and its vertical distribution within the cloud affected by the synoptic low-pressure systems. Despite these studies on cloud properties in Iraq, there is a lack of detailed spatial analysis focusing on cloud base height, total cloud cover, and the distribution of high, medium and low clouds.

Most existing research overlooks regional variability and spatial patterns across Iraq's diverse climatic zones. Studying cloud properties in Iraq is crucial for improving climate monitoring, weather forecasting and water resource management in a region facing arid conditions and the impacts of climate change. It supports better agricultural planning, enhances solar energy development by assessing the impact of clouds on sunlight, and contributes to environmental and atmospheric research. Overall, cloud studies provide valuable data for sustainable development and disaster preparedness. This gap limits our understanding of cloud dynamics and their impact on agriculture and water management. A comprehensive spatial study is therefore needed to address these limitations and support improved environmental planning. The aim of this paper is to study the variation in the annual monthly distribution of cloud properties, including cloud base height, high, medium and low clouds, and total cloud cover over Iraq using ECMWF ERA5 data for the period (2010-2019).

MATERIAL AND METHOD

Study Aera

Iraq lies between 29.0° to 37.2° N latitude and 38.7° to 48.7° E longitude, as shown in Fig. 1, and has a diverse topography that can be divided into four main geographical regions: 1) the mountainous region (northeast), including the Zagros Mountains, located along the borders with Iran and Turkey with an elevation of more than 3,000 m above mean sea level (msl), 2) the north and northwest region, where a zone of rolling hills and upland plains with moderate elevation lies. The alluvial plain in the central and south-eastern region is characterized by flat and low-lying areas between the Tigris and Euphrates rivers at an elevation of 100 m above msl, and 4) the western desert, which covers about 40% of Iraq's lands and is dominated by arid desert and rocky plateaus. Iraq's climate is subtropical, continental, arid to semi-arid with dry hot summers and cooler winters (18). The rate of rainfall is low in central and southern of Iraq (100-200 mm) but it is high in north, which reach about 1000 mm and falls in November to April (19). About 90% of the annual rainfall falls in the winter months of December to March. The remaining six months, especially the hottest months of summer (June-August) are dry with no rain at all.

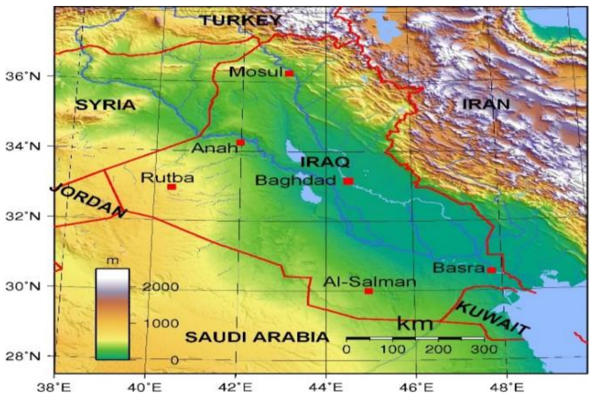


Fig. 1: Map of Iraq with its surface topography (18).

Source of Data

The monthly cloud properties data, including cloud base height, cloud cover types with their height, for the period from 2010 to 2019 have been obtained from the ECMWF ERA5. ERA5 is the fifth generation of ECMWF reanalysis data for global climate and weather for the last 4 to 7 decades. Data are currently available from 1950 onwards, split into Climate Data Store entries for 1950-1978 (preliminary back-extension) and from 1979 onwards (final release plus timely updates). The accuracy of ERA5 data for certain cloud-related parameters varies depending on spatial and temporal scales, observational comparisons and the nature of the parameter. However, ERA5 is considered reliable for climate and weather research, especially for large-scale analyses and model validation, while it improves on its predecessor, ERA-Interim, by incorporating a more advanced data assimilation system (4D-Var) and a larger volume of observations (20)(14).

METHODOLOGY

One of the most important cloud characteristics is the cloud base height (CBH), which is the height above the Earth's surface at which the lowest layer of a cloud begins to form. In other words, it's the height of the bottom of the cloud layer where the air becomes saturated and condensation begins. In the ERA5 reanalysis dataset, CBH is estimated using atmospheric profiles (temperature and humidity) and cloud information derived from the data assimilation system. Low CBH is often associated with fog, low visibility or poor flying conditions. Cloud cover is the fraction of the sky obscured by clouds at a given location and time. It quantifies how much of the sky is covered by clouds. It is usually expressed as a percentage (%) or in eighths (oktas) of the sky dome, ranging from 0% (or 0 oktas) for a clear sky to 100% (or 8 oktas) for a completely cloudy sky. It is an important meteorological parameter used to describe weather conditions and predict climate behaviour. Clouds are divided into three main categories based on the height at which they form in the atmosphere. The main categories are low (surface to ~2 km), middle (2-7 km), high (5-13 km) and vertical clouds. Each group has different characteristics and weather implications. Total cloud cover (TCC) is defined as the fraction of the sky covered by clouds in all vertical layers of the atmosphere. Their data have been obtained from ECMWF ERA5 and are available digitally in the form of a NetCDF file. The data was analyzed and displayed using the Grid Analysis and Display System (GrADS) (21). The process data includes CBH, cloud cover for high, low, medium and TCCs. Spatial analysis of these cloud properties examines how different cloud characteristics vary across geographic regions and time. This type of analysis is key to understanding atmospheric processes, climate variability and weather systems. To identify consistent annual patterns of these cloud properties, monthly means were calculated for the period 2010-2019 using reanalysis datasets. The monthly means were then averaged over all years of the 10-year period for each calendar month. All statistical analyses were performed in Excel.

RESULTS AND DISCUSSION

Spatial Variation of Cloud Base Height

Studying the variations in CBH not only affect the accuracy of weather forecasting, but also have implications for aviation, the radiation budget, and precipitation processes. The results of the monthly average variation of the CBH from the Earth's surface over Iraq for each month of the year (from January to December) over the period (2010 to 2019) are shown in Figs. 2a-l, respectively. The scale bar at the bottom (in km) represents the height of the CBH. The maximum level of CBH was found in the south of Iraq, while the minimum level was found in the north. This is because the southern region is considered to be the hottest region, while the northern region is considered to be colder than other regions in Iraq. It is also clear that in the months of January, February, March, November and December the CBH is low in the northern and western regions. The spatial distribution of CBH shows significant seasonal variability, which is closely related to atmospheric stability, surface heating and regional topography. During the winter months (December to February) the CBH is lowest, particularly in the northern and northeastern regions, where values often fall below 4.5 km (see Figs. 2l,a,b). This pattern is consistent with the presence of cold air masses, frequent frontal systems and increased atmospheric moisture, which favour the formation of low to mid-level clouds. The lower CBH in the north is also likely influenced by the Zagros mountain range, which enhances orographic lifting and contributes to cloud formation at lower altitudes.

As Iraq transitions into spring (March to May), CBH values increase, with the southern and central parts of the country experiencing heights above 6 km by May, as shown in Fig. 2e, because this May is characterised by high temperature and the southern region is considered the hottest region, while January is characterised by low temperature and the northern region is considered a colder region than other regions. This reflects the increase in solar radiation, surface temperatures and convective activity, which together increase the lifting condensation level and result in higher cloud bases. The most dramatic increase occurs during the summer months (June to August) when CBH values peak over most of the country (see Figs. 2f-h), particularly in the central and southern regions where values exceed 7.5 km. This is a result of intense surface heating under dry conditions, leading to deep convective development when moisture is available. However, the presence of large white patches during these months – especially July and August – shown in Figs. 2f-h suggests very sparse low and mid-level clouds due to the dominance of clear skies. The results also indicate that there is no cloud activity over Iraq during June, July and August. In autumn (September to November), the CBH gradually decreases as atmospheric instability decreases and surface temperatures decrease. This seasonal decline marks a return to conditions favourable to the development of low-level clouds, particularly in north. Notably, the spatial distribution of CBH maintains a persistent gradient throughout the year: the northern and northeastern regions consistently show lower CBH values compared to the south and west. This highlights the combined influence of Iraq's topographic variation and latitudinal climate gradient.

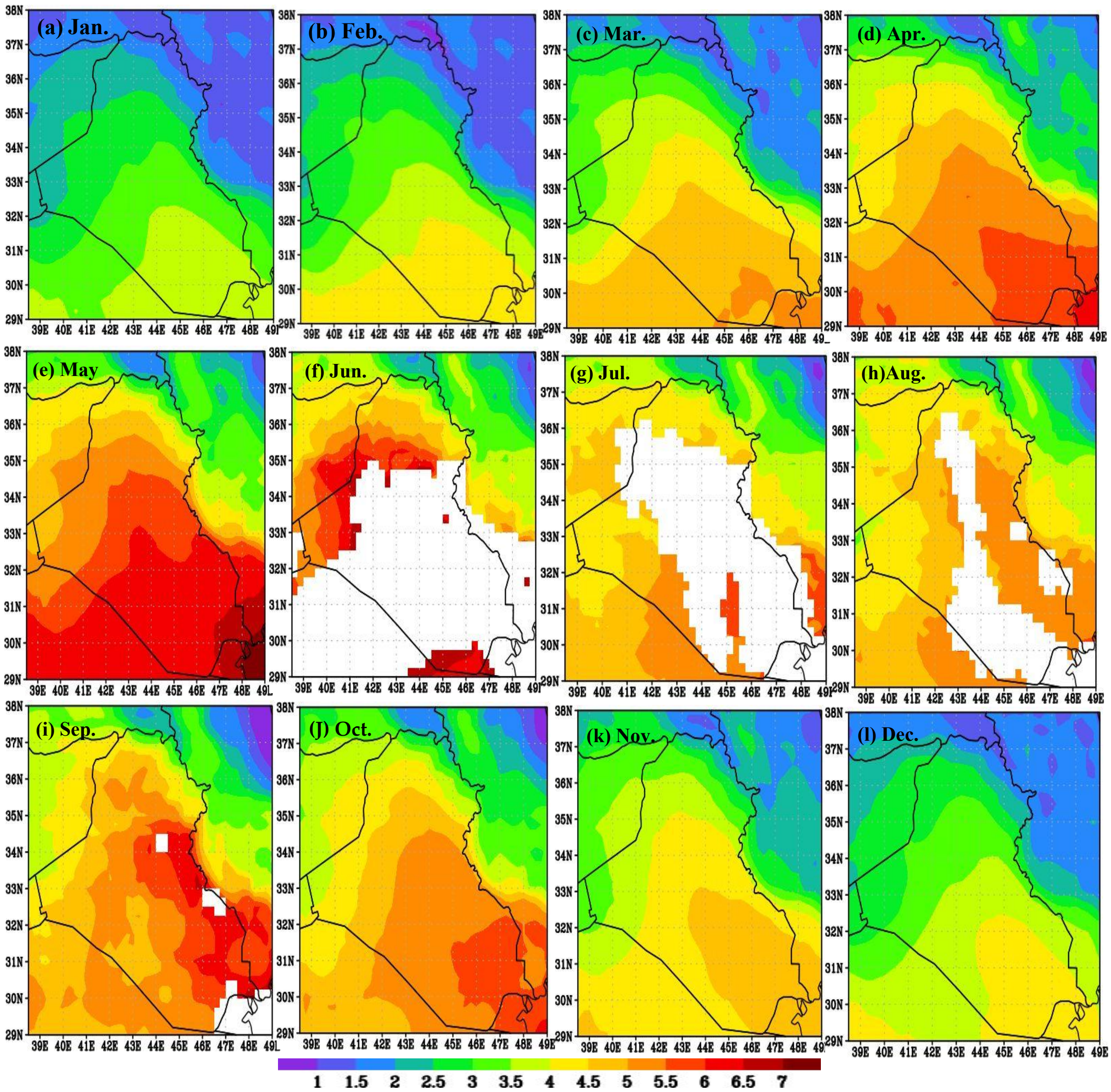
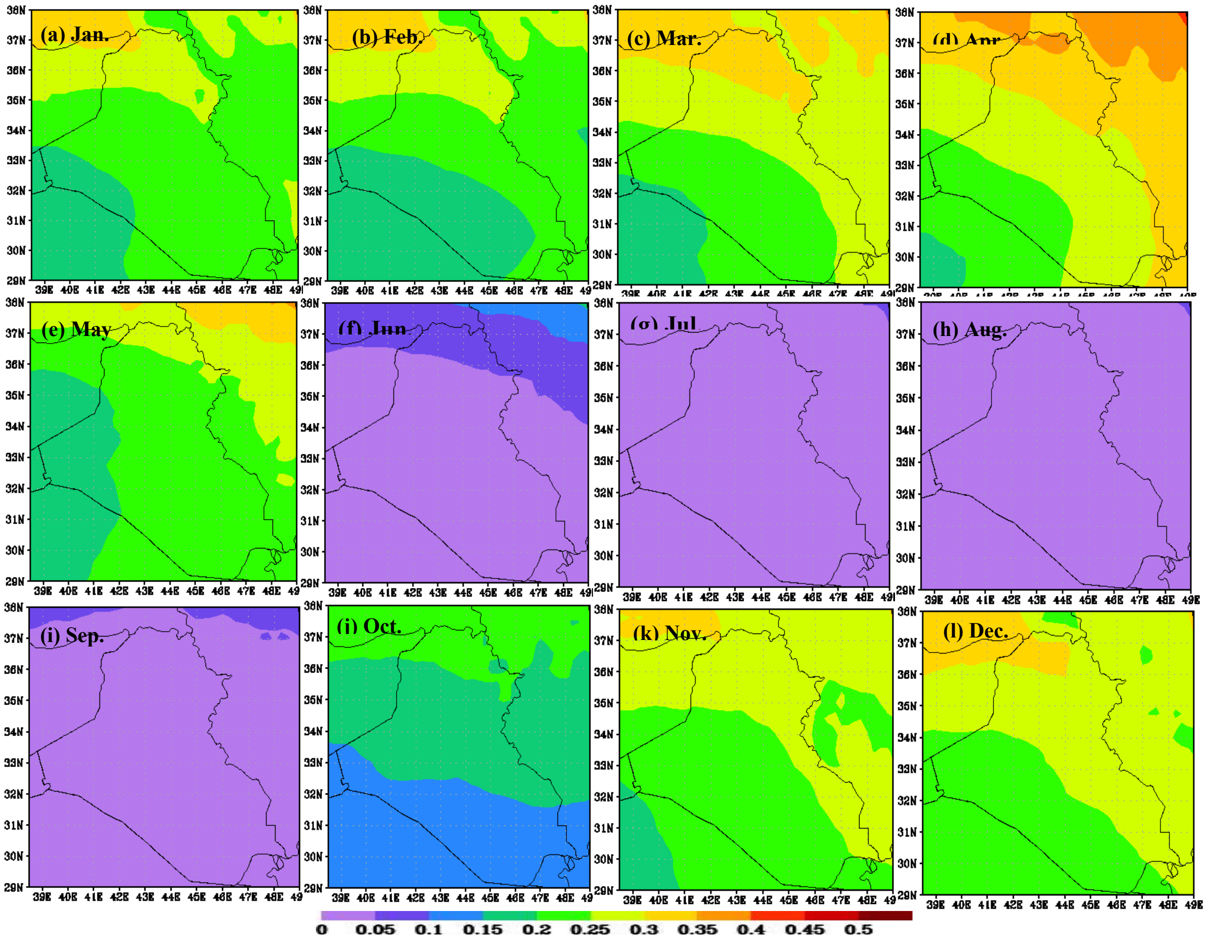


Fig. 2: The monthly varation of CBH (in km) over Iraq.

Spatial Variation of High, Meduim and Low Cloud Covers

Figs. 3a-l show the monthly high cloudiness over Iraq for 10 years. It is clear that the northern region was covered by a higher fraction of high cloud than the other regions, and the low fraction of high cloud occurred in the southern regions. The variation of monthly HCC shows a clear seasonal pattern with significant spatial differentiation. During the winter and early spring months (January to April), HCC is relatively more frequent, especially in the northern and northeastern regions, with values ranging from about 0.15 to 0.35, as shown by the green and yellow shades (Figs. 3a-d). This increased presence of high clouds during the colder months is probably related to upper-level frontal systems and jet stream activity, which are more prevalent during this period (22). Moving into May and June, there is a sharp decline in HCC over much of the country shown in Figs. 3e and f, particularly in the central and southern regions where values drop below 0.05 (represented by purple shades), indicating a transition to drier, more stable atmospheric conditions.

Figs. 3f-h show the lowest occurrence of HCC during the summer months (July to September), with the entire country mostly dominated by values close to or below 0.05, reflecting the dominance of clear skies due to intense surface heating and limited upper-level moisture. This minimal high cloud presence coincides with Iraq's dry season, which is characterised by subsidence and stable atmospheric profiles that suppress cloud formation at high altitudes. A modest increase in HCC begins in October, particularly in the northern areas (Fig. 3j), and this trend continues into November and December, with values increasing again in the northeastern and central regions. This seasonal return of upper-level clouds indicates the onset of transitional weather systems and increasing moisture associated with the approaching winter season. Overall, HCC is most pronounced during the cooler months (November to April) and significantly reduced during the hot, dry summer months, highlighting the influence of large-scale atmospheric circulation and seasonal thermal dynamics on upper-level cloud development in the region.



The spatial distribution of annual mean MCC over Iraq from 2010 to 2019 shows a distinct inter-annual variability and a north-south spatial gradient, as shown in Figs. 4a-l. It is evident that the northern region is characterised by the highest MCC coverage compared to other regions. The months of May and October were characterised by a minimum coverage from the MCC fraction less than 0.15, which occurred over all Iraqi regions, while the months of June-September showed that there are no cloud activities happened during these months. During the winter and early spring months (January to April), this cover type is most prominent, especially in the northern and northeastern regions, where cover values exceed 0.4 in January and February, as shown by the orange and red shading (Figs. 4a-d). This pattern is attributed to the increased frequency of weather systems and the interaction of moist air masses with the elevated terrain of northern Iraq, which favours the development of mid-level stratiform and altocumulus clouds. As we move into late spring (May), Fig. 4e shows that the MCC decreases significantly across the country, with values generally falling below 0.15, particularly in the central and southern regions, indicating a transition to drier atmospheric conditions.

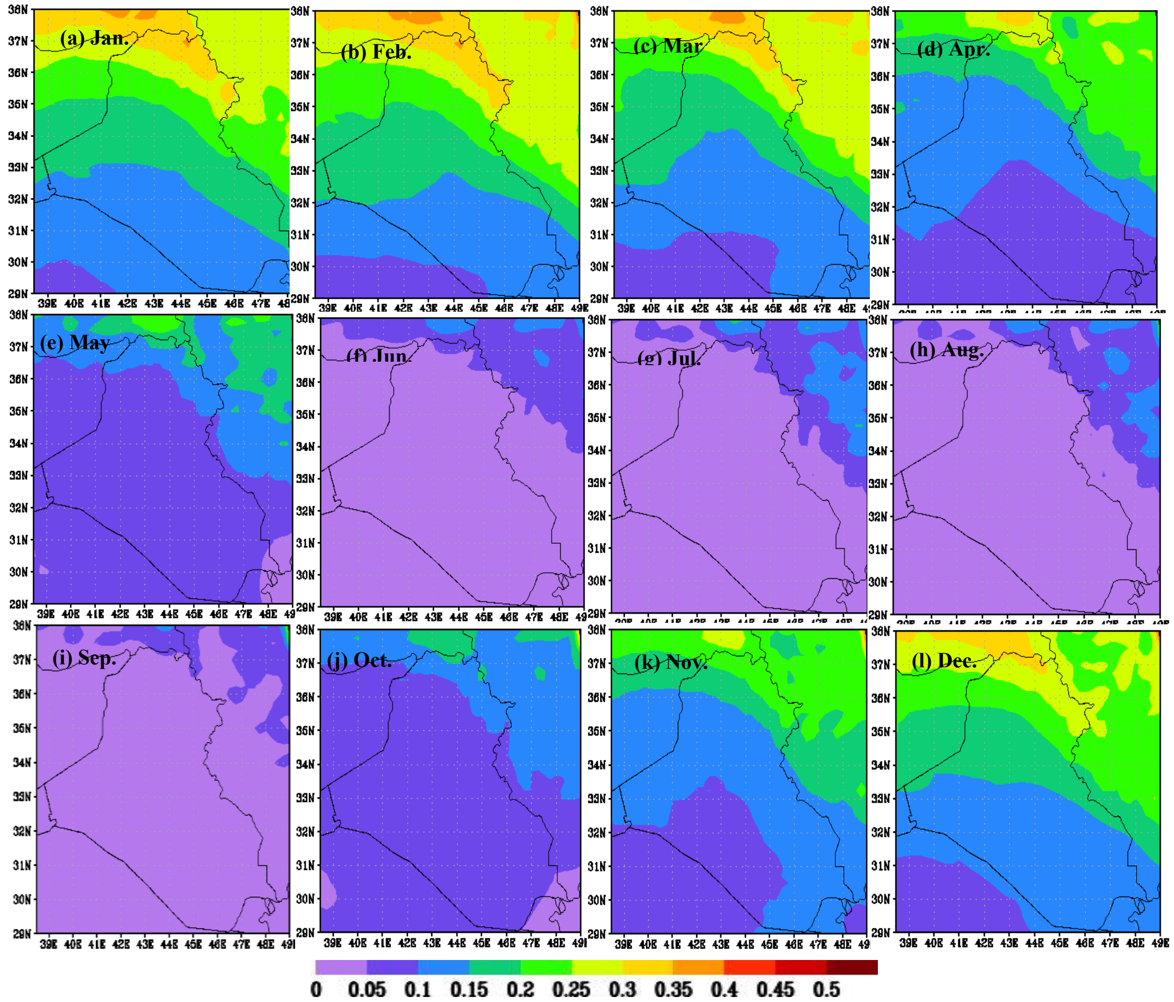
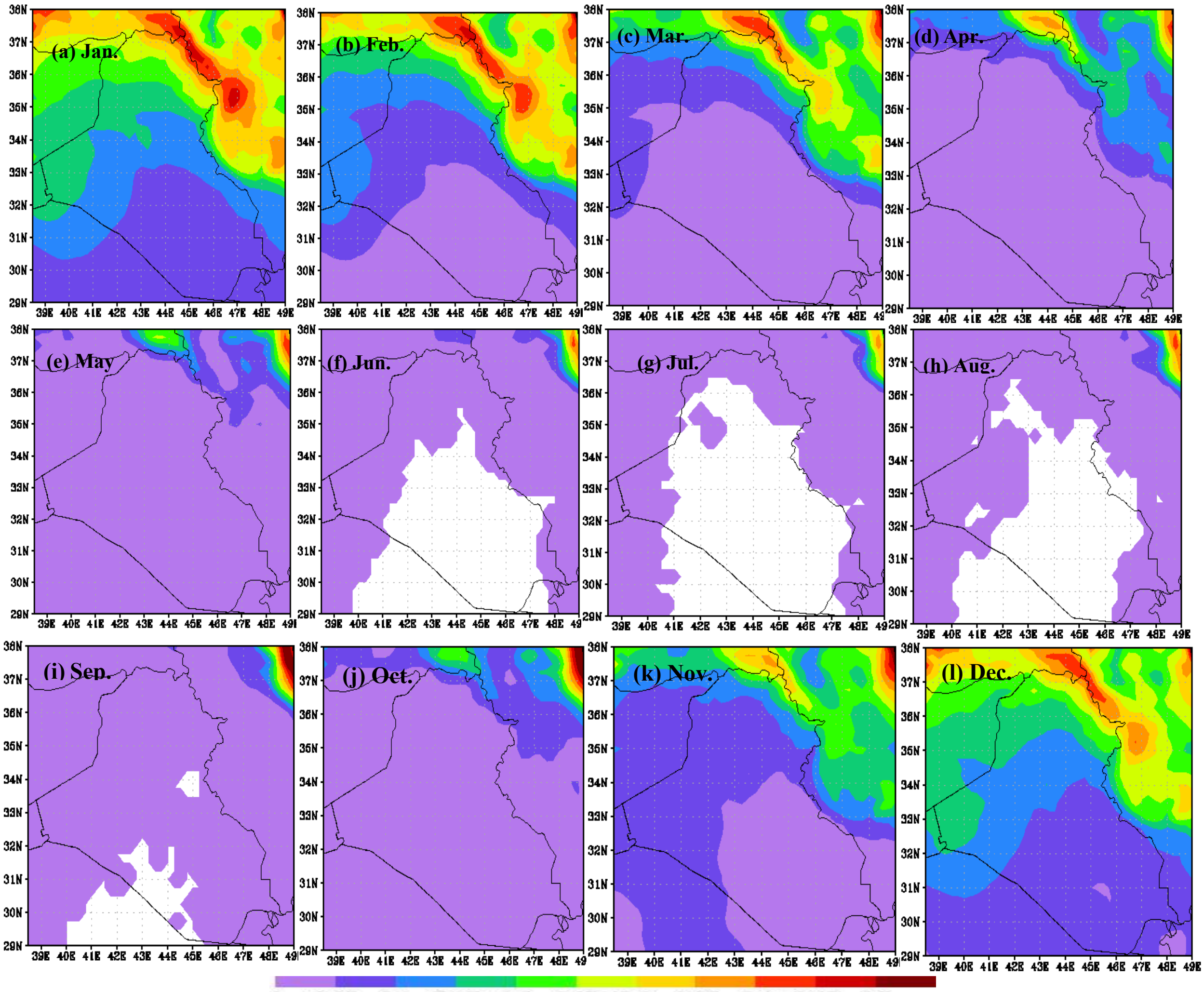


Fig. 4: The spatial variation of monthly MCC (fraction) over Iraq.

During the summer months (June to September) the MCC reaches its lowest values in all regions, with most of the country having coverage values below 0.05 (dominated by purple shades, see Figs. 4g-i). This decrease reflects the dominance of high pressure systems, strong surface heating, and minimal midlevel moisture, all of which inhibit the formation of midlevel clouds. Interestingly, a slight increase in localised MCC appears along parts of the northeastern boundaries in August and September, possibly due to weak convective activity. In October and November, shown in Figs. 4j and k, MCC gradually increases again, especially over northern Iraq, as frontal activity resumes and midlevel atmospheric conditions become more conducive to cloud formation. By December, the MCC has returned to winter-like conditions, with coverage again reaching around 0.3-0.45 in the north (Fig. 4l). Overall, the northern and northeastern regions consistently experience more MCC throughout the year compared to the south and west, reflecting both topographic effects and latitudinal climate gradients. The results indicate that MCCs are most abundant during the cool, wet season and sparse or almost absent during the hot, dry summer months.

Figs. 5a-l illustrate the monthly average distribution of LCC across Iraq for 12 months over the period 2010-2019. The results show that the highest low cloud coverage occurred in the northern region, while the lowest coverage occurred in the southern region. The data for LCC are coloured with purple indicating low values and shades progressing to red for higher cloud cover. During the winter months: December, January and February, there is a noticeable increase in LCC reaching approximately (0.45), especially in the northern and northeastern parts. In January and December, cloud cover peaks, especially along the Zagros Mountains near the borders with Turkey and Iran. These areas are marked with orange and red tones, corresponding to values above 0.45 and even up to 0.65 in some places. This high cloudiness is due to active weather systems from the Mediterranean bringing precipitation and cooler air masses, which favour cloud formation. February also shows an increased cloudiness, but slightly less than the surrounding months.



Spatial Variation of Total Cloud Cover

Figs. 6a-l presents the annual monthly variation of TCC at 12 months (January-December). Each panel represents one month and illustrates how TCC varies spatially and seasonally across the country. A gradual decrease in TCC is observed in spring. March and April show moderate cloudiness in the north, while central and southern Iraq begin to clear up, as indicated by the dominance of violet and blue hues, which represent values below 0.25. In May, most of the country experiences very low cloudiness, with large regions showing values below 0.1. This reflects the transition to the dry season, when sinking air and rising temperatures reduce the likelihood of cloud formation. The summer months of June, July and August are characterised by minimal low cloudiness throughout the country. Large parts of Iraq, particularly in the central and southern regions, are shown in white, indicating almost no cloud cover. This period coincides with Iraq's extremely hot and dry season, which is dominated by strong solar heating and sinking air from the subtropical high pressure system. Cloud suppression is most extreme in July, the hottest month, when even the northern regions show minimal cloud presence. With the onset of autumn, cloud cover remains low in September, but begins to increase gradually in October. Northern and northwestern Iraq begin to experience moderate cloud cover, signalling the end of the dry season. This trend continues into November, which shows a significant return of low cloudiness in the northern parts, with values rising back above 0.25 in many areas. This increase reflects the reactivation of the Mediterranean-influenced weather pattern, which brings cooler air and moisture leading to cloud development.

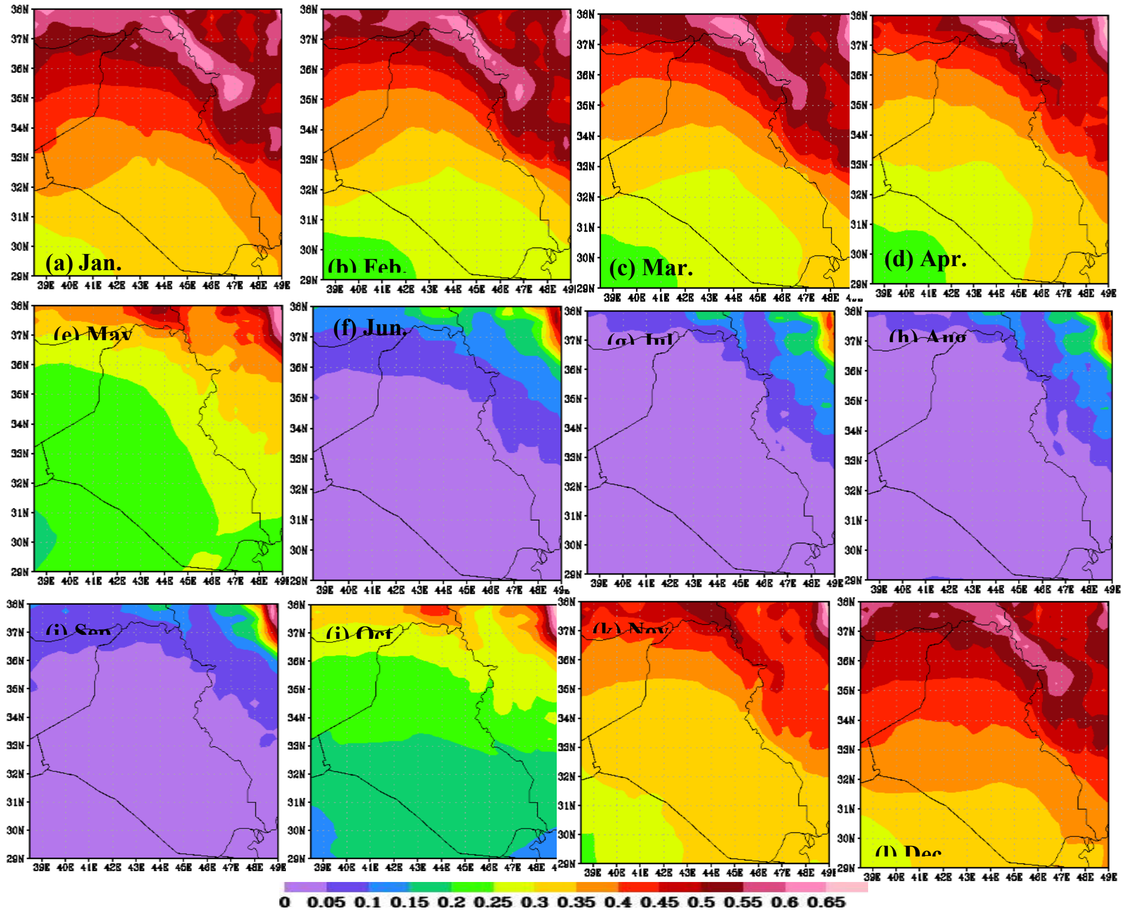


Fig. 6: Spatial distribution of total cloud cover (fraction) over Iraq.

The colour bar at the bottom ranges from white (lowest cloud cover) to dark red and pink (highest cloud cover), with values between 0.05 and 0.65. This comprehensive visualisation highlights the TCC patterns that govern cloud development over Iraq throughout the year. During the winter months (January-December), the TCC is at its highest, particularly over northern and northeastern Iraq, where values exceed 0.6, shown in dark red and pink shades. This region, influenced by the winter activity tracks of the Mediterranean and the orographic uplift of the Zagros Mountains, experiences dense cloud cover throughout. Central and southern Iraq show less cloudiness, with values gradually decreasing to 0.25-0.4, shown in yellow to orange tones. These months coincide with the region's rainy season, which brings significant rainfall and increased cloudiness. As the country moves into spring (March-May), there is a gradual reduction in cloud cover. In March and April (Figs. 6c-d), the north still retains considerable cloudiness with values around 0.45-0.55, but the central and southern regions continue to clear, moving into the yellow and green zones (0.15-0.35). By May (Fig. 6e), TCC has decreased significantly over most of Iraq, with only the former extreme north showing moderate cloud presence. This decrease reflects the shift to drier atmospheric conditions. During the summer months: June, July and August, minimal TCC was recorded over Iraq, with values between 0.05 and 0.15 over most of the purple and blue coloured country, with only the extreme north and north-east receiving slightly higher values due to some orographic or convective influences. This period coincides with high temperatures, strong solar radiation and stable atmospheric conditions that suppress cloud formation.

CONCLUSIONS

This study provides a comprehensive analysis of the spatial distribution of cloud base characteristics over Iraq. The average conclusions from this paper are the maximum cloud base height above 6.5 km occurred in May over the southern region, while the minimum height below 2.5 km occurred in January over the northern region. In April, the north area had the greatest amount of ceiling above 0.35, while the south area had the least amount of ceiling below 0.15. The coverage of medium cloud is highest in the northern region than in other regions, reaching 0.3 in January-March due to frequent weather systems and topographic influences, while it is minimal during the hot summer months (June to September), with the southern and central regions experiencing the least cloud activity. The northern part of the country has the highest percentage of low clouds, around 0.45 in the winter months, while the southern part has the lowest, below .1 in December and January. The TCC of the northern region was higher than other regions and reached approximately to 0.6 in January, February, March, April, November and December. The results show that there is no cloud coverage over all regions in Iraq for the types of high and medium cloud in June-September, while low cloud disappeared from May-October because there are no cloud activities occurred in these months.

The results indicate that cloud cover in Iraq is highly seasonal, with the highest values observed during the winter months (December-February), particularly in the northern and northeastern regions, due to the influence of Mediterranean and Red Sea weather systems and orographic uplift associated with the Zagros Mountains. Conversely, the summer months (June to August) are characterised by minimal cloud cover over most of the country, reflecting the dominance of stable, dry and hot atmospheric conditions during this period. A more detailed study combining CBH with cloud type classification, vertical profiles and atmospheric moisture content would improve our understanding of the role of clouds in Iraq's changing climate. This information is valuable for understanding Iraq's weather behaviour, supporting climate-related studies, informing agricultural and water resource management, and energy sustainability, making it a valuable focus for national and regional development strategies.

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Conflict of Interest

The authors declare no conflict of interest

Authors contrbutions

All authors contributed to the concept and design of this work. Data collection, Material preparation, and analysis were carried out by N.T. Ibraheem, Z.N. Al-Montaser. The first draft of the manuscript was written by M.F. Al-Zuhairi and M.H. Al-Jiboori.

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