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RESEARCH ARTICLE

Evaluating Climate Sensitivity to Atmospheric CO_2 in Basra, Baghdad and Mosul: Iraq

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ABSTRACT

Iraq has been suffering from a rising surface air temperature (SAT), causing a general deterioration in ecosystems. Climate sensitivity (CS) which refers to the increase in average SAT caused by a duplication of Carbon Dioxide Concentration [CO_2], was estimated by transient local climate response (TLCR) and equilibrium local CS (ELCS). The time series of the spatial annual averages for both [CO_2] and air temperature were analyzed and a linear regression model was also used to find annual trends in SAT and [CO_2]. Based on historical yearly data for CO_2 concentrations (2003–2016), CO_2 emissions (2000–2021), and SAT (1971–2022), CS is evaluated concerning three main areas in Iraq: Basra, Baghdad, Mosul and the whole of Iraq. The results showed that yearly mean SAT and [CO_2] in Iraq were well fitted by the regression model with the values of 2.11 ppm/year and 0.07 °C/year, respectively. Among the selected provinces, the highest upward trends in SAT and [CO_2] were observed in Basra with the values of 2.15 ppm/year and 0.09 °C/year, respectively, mainly caused by the doubling of CO_2 emissions from 70 Gt in 2000 to 150 Gt in 2021. The result also shows that the TLCR and ELCS values in Iraq are 2.55 and 3.8 °C, respectively, within the range suggested by the IPCC 5th Assessment Report for Iraq.

Keywords: Climate sensitivity, Climate trend, CO_2 concentration, Emission rate of CO_2, Surface air temperature

Introduction

Due to global warming over the past two decades, the Republic of Iraq has faced several difficulties and challenges in various sectors of life, especially extreme weather events and changes in climate patterns. One of the most significant phenomena is the increase in surface air temperature (SAT), which is rising sharply, with the highest recorded in Basra at nearly 52 °C.[1] In addition to environmental changes, climate change in Iraq poses a serious threat to basic human livelihoods, creating barriers to sustainable development and exacerbating the country's social and economic challenges.

Carbon dioxide (CO_2) is considered to be the most important greenhouse gas (GHG), contributing to about 2/3 of human-induced global warming. The main source of CO_2 emissions into the atmosphere is anthropogenic.[2] Other GHGs, like Methane, Nitrous oxide, water vapor, and Chlorofluorocarbons also cause this effect, although CO_2 is the main responsible gas. Since the beginning of the industrial revolution, CO_2 levels have gradually increased over the past two centuries. As more CO_2 enters the atmosphere, it can cause global temperatures to rise.

Climate sensitivity (CS) is the response of the global mean SAT to possible changes in the CO_2 concentration [CO_2] in the atmosphere.[3] An accurate assessment of the climate response is required to assess the impacts of climate change and to inform policy. CS cannot be measured directly, but must be evaluated using three wide approaches: historic observations,[4] numerical models[5] and palaeoclimatic data.[6] In the last two decades and under the ongoing global warming, Iraqi society has become increasingly concerned about the frequent consequences

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observed as a result of rising air temperatures such as extreme temperatures, heat waves, severe droughts, sand and dust storms, rainfall variability, water scarcity, salinity threatening for agriculture, especially in the central and southern part of the country. All of these consequences have already led to high rates of heat-related mortality in public health[7] and food security.[8] To avoid exacerbating these threats, there is an urgent need to explore the estimation of CS for future action.

Generally, some natural factors influence SAT at a specific site: latitude, elevation, and distance from water bodies, air circulation, and local aspects.[9] Their effects diminish at local scales of long-term time series.[10] Radiation forcing (ΔF) is the difference between the radiation received and radiated at the upper atmosphere, which is due to the temperature variation compared to a reference forcing variation.[11] Human activities have caused changes in radiative forcing. For example, increases in [CO_2] increase the net ΔF by decreasing transparency on heat radiation, giving rise to a warming of the climate.[12] However, there is evidence that CO_2 levels can vary over long periods, causing significant climate changes. Scientists try to determine this by evaluating how much the world average SAT would vary if CO_2 levels were duplicated, which would roughly raise it (~3 °C).[13] This is subject to relatively large uncertainties.[9] A higher CS value would indicate more significant temperature increases and more expected alterations in weather patterns.

Many previous studies have described the warming climate over Iraq in terms of temperature trends over different long time periods,[14,15] but a very limited number of studies have been carried out on the ongoing temperature increase due to [CO_2]. Two studies have been carried out[16,17] for predicting long-term climate change in which the future annual mean SAT was projected for four years: 2025, 2050, 2075, and 2100 using coupled model inter-comparison project phases under different scenarios of representative concentration pathways. They expected that the annual mean SAT to increase dramatically with temperatures between 1 and 4 °C above the current mean SAT. Hebert and Shaun[18] developed a method based on the transient climate sensitivity (TCS) estimations at the regional scale ($5^\circ \times 5^\circ$) and historical simulations made by global climate models and the linear relationship between the forced temperature response and the anthropogenic forcing. They concluded that the historical method is more relevant. Meanwhile, Sherwood et al.[19] issued a review to assess multiple lines of evidence including human influence on the TCS range (1.5–4.5 °C) per 2x[CO_2]. They found that a big volume of consistent evidence now points to a more confident interval of CS, especially, near the middle or upper part of this range. In Iraq, Ibraheem et al.[15] analyzed 40 years (1971–2021) of observational yearly mean SAT records over three major cities: Basra, Baghdad and Mosul. In summer, their highest values reached 40 in Basra and 35 °C in Baghdad and Mosul. The rise in SAT was attributed to the increase of 5 times after 2000 compared to the before.

Unfortunately, over the years the Iraqi government has severely neglected the industrial sector, focusing primarily on the oil industry because Iraq is known as a highly oil-dependent nation with no other developed sectors. As a result, the industrial sector has become increasingly dependent on oil money.[20] The main objectives of this work are to 1) examine the time series for the above variables with a determination of the trend, 2) evaluate the local response to alterations in [CO_2], and 3) evaluate the number of CS resulting from alterations in [CO_2] that require mitigation and adaptation activities for future changes.

Materials and methods

Study area and data

This paper was carried out in three major provinces in Iraq that are located in the Middle East with a total area (=437072 km^2). The main land cover is desert with about 73% and the remaining parts are often composed of agricultural land (23%), urban and suburban areas (3%), and water bodies (1%).[21] Iraq's topography is characterized by mostly broad plains, with large desert plateaus dominating the west of the country. Iraq is located at latitudes 29.5–37.5° N and longitudes 38.45–48.45° E and is bordered by Turkey to the north, Iran to the east, Kuwait to the south, Saudi Arabia to the south-east, Jordan to the west and Syria to the northwest (see Fig. 1). Elevations vary widely, from remnants of sea level in the southeast (reedbed oases) to mountains reaching 3583 m in the north and northeast, bordering Iran and Turkey.[22] Two rivers, the Tigris and the Euphrates, flow from Turkey to the southeast, which join the Shatt-Al-Arab. They irrigate the lowlands in the central and southern parts of the country, while the highlands are mainly rain-fed.[23]

For this paper, Iraq was divided into 3 main regions: south, center and north, represented by the major cities: Basra, Baghdad and Mosul, respectively. These are the most populous cities that contribute heavily to the total population.[24] Table 1 presented the geographical coordinates, elevation above sea level, and the population density (in pop/km^2) data for all studied provinces (in 2022) calculated by dividing the

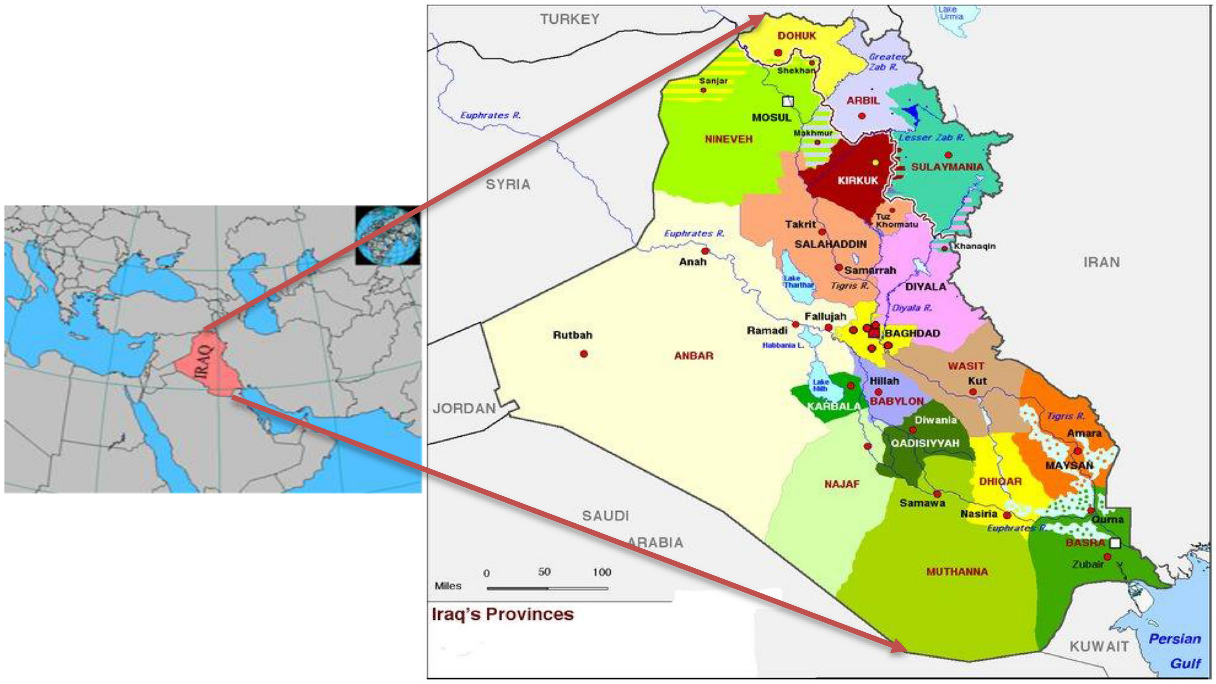

Fig. 1. Map of Iraq with study areas marked with squares: Basra, Baghdad and Mosul.

Table 1. Latitude, longitude, and elevation of studied provinces and their population density for the year 2022.

Province	Latitude (°) E	Longitude (°) N	Elevation (m)	Population density (pop/km^2)
Basra	30.5	47.8	5	160.6
Baghdad	33.3	44.4	34	187.9
Mosul	36.3	43.2	223	105.2

number of people by the area. The capital, Baghdad, ranked first as the most densely populated city in Iraq during the year 2022, then Basra and lastly Mosul. The overall climate of Iraq is semi-arid to arid, with hot summers and cooler winters. The average yearly SAT is between 10 in winter to 38 °C in summer. Precipitation falls between November and April, with a yearly mean between 140 mm in the south to 380 mm in the northeast areas. The prevailing wind direction is north-westerly with an average yearly velocity of 3.5 m/s.[25]

This paper collected data available on popular websites, such as annual [CO_2] and emissions, and real records of yearly SATs in three cities with different characteristics in Iraq: south (Basra), center (Baghdad), and north (Mosul). Three datasets were used; first, monthly CO_2 concentration data obtained from the NASA-operated GIOVANNI portal with 2° × 2.5° spatial resolution ascending orbits were downloaded from the link (www.disc.sci.gsfc.nasa.gov/giovanni) for fourteen years (2003–2016) for three points within the above cities. Unfortunately, this website contains only these available years and is not found elsewhere in the informal Iraqi agencies. The [CO_2] data were obtained from ascending orbits with a spatial resolution of 2° × 2.5° (latitude × longitude). Monthly concentrations were summed over 12 months to calculate annual means. Second, yearly mean SATs for the above cities were obtained from the Iraqi Meteorological Service for fifty-two years (1971–2022). Third, annual rates of total CO_2 emissions for 22 years (2000–2021) were obtained from the Our World in Data website (https://ourworldindata.org), which is supported by the Global Carbon Project. These emissions represent all types of emissions, including coal, oil, gas, cement, and flaring industries.

Research methods

The response of CS to changing atmospheric CO_2 concentrations can be considered as a ΔF agent when assessing climate change. Through the simple equilibrium model, it can have a direct and indirect impact on the change in surface air temperature (ΔSAT)[26]

$$\Delta SAT_j = -\frac{\Delta F_j}{\varphi} \quad (1)$$

ϕ is a parameter of the climate response and j is a forcing agent. ΔF involves the anthropogenic and natural activity contributions. The latter has a small effect,[10] while the former has significant impacts.[19] Yearly changes of $[CO_2]$ as a function of anthropogenic forcing have been included in this paper. One or two of j are widely used to evaluate the SAT response using numerical simulations, like general circulation or regional climate models; investigation of each active ingredient leads to a challenge in the uncertainty of that estimate. For future years, these data can be derived by interpolation using the trend analysis over a given time described in the following subsection. In a review paper, Sherwood et al.[19] showed that estimates of CS can be achieved not only by future climate projections, but also by analyzing relevant observational data, such as statistical Bayesian approaches.[27] Therefore, the present study attempts to determine the local climate response using historical yearly $[CO_2]$, CO_2 emissions, and mean SAT, that can account for the local effects in a global climate without relying on climate models.

CS is usually described in two ways, following the timescale of concern, which are the transient local climate response (TLCR) and the equilibrium local CS (ELCS). The first is the increase in local yearly temperature at the time that would be predicted if atmospheric $[CO_2]$ doubled at a rate of 1% per year. This was evaluated by Smirnov[28]

$$TLCR = \alpha * (SAT_2 - SAT_1) * \frac{log\,(2)}{log\left(\frac{C_2}{C_1}\right)} \quad (2)$$

where α is attribution to anthropogenic CO_2 (accounted here 50%). C_1 and C_2 are also the starting and ending $[CO_2]$ at the same interval. That estimate applies to the middle of short yearly periods of SAT (e.g., at least twenty years) of duplicated atmospheric CO_2.

The second is an assessment of the progressive steady-state local increase in temperature following the determination of the TLCR expected from a doubled $[CO_2]$. On other speech, as the $[CO_2]$ exceedance has stopped and the responses have had time to have their full effect, an assessment can be made of the likely long-term SAT. Due to the short-term buffer influences of the ocean, ELCS values are often higher than TLCR values.[1] According to the 5th Assessment Report IPCC, the ECS is "likely" within the interval from 1.5 to 4.5 °C,[29] whilst the TCR is likely to be between 1 and 2.5 °C,[4] and hence ELCS evaluated as

$$ELCS = 3 * TLCR/2 \quad (3)$$

Monthly data for both $[CO_2]$ and SAT were used to calculate yearly averages for each province. These were calculated by adding and dividing by 12 months. Spatial yearly averages of Iraq were also computed by adding the yearly means of cities studied divided by three. Although these averages may not be sufficient to represent the whole of Iraq, they could provide reasonable results, especially for air temperature, whereas most of the interior of Iraq consists of roughly flat land with a percentage of 99.8% of the total area, while the averages for atmospheric $[CO_2]$ are more corrected due to the rapid mixing in the atmosphere. The standard deviation has been calculated. It is represented by the vertical lines in the figures. Scatter plots were used to show the variation of CO_2 and SAT over a period, and then the linear regression model for predictive analysis involves testing relation strength among $[CO_2]$, emitted rate, and ΔSAT, which also has the benefit of being able to predict an effect and trends, which can be written as follows[30]

$$y = \gamma + \beta * x \quad (4)$$

where y is the variables: $[CO_2]$, CO_2 emission rate, or local SAT. and x is the studied years. The constants γ and β are the intercept and the slope (or trend), respectively. The derived trends are important given the climate research towards understanding historical patterns and predicting what will happen in the future. Fig. 2 shows the flowchart of the presented paper. The determination of coefficient, R^2, was computed to measure how well the Eq. (4), predicts the dependent variables. Finally, the following equation is used to evaluate the absolute increase, which is a measure of how much a given level of $[CO_2]$ emissions will change in the atmosphere over a given time

$$Percent\ of\ change\ (\%) = \left|\frac{C_2 - C_1}{C_1}\right| * 100 \quad (5)$$

The absolute amount was used here to omit negative values in some cases.

Results and discussion

Yearly variation of $[CO_2]$ and SAT

Yearly variations in atmospheric CO_2 concentrations in Basra, Baghdad and Mosul are displayed in Fig. 3a–3c, respectively, except 2015 and 2016, σ values are low. The linear rise can be seen for all,

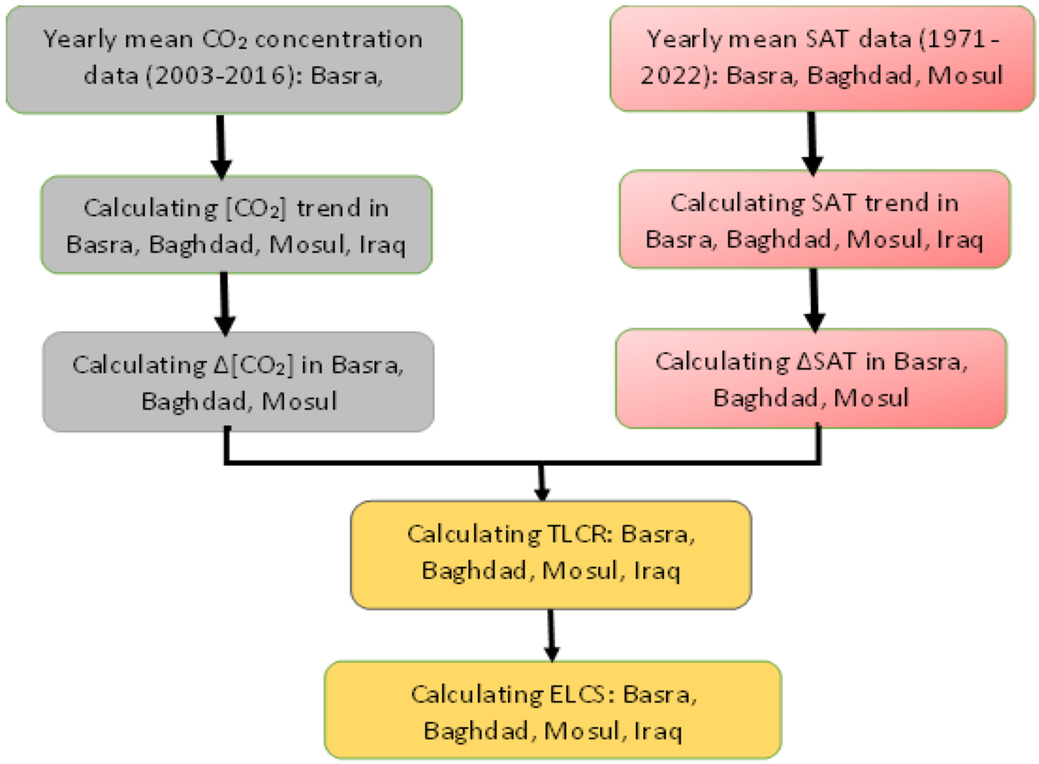

Fig. 2. Flowchart of methodology.

but the slope is different. The constants γ and β were determined from the yearly $[CO_2]$ data by drawing the best-fitting lines using Eq. (4). The values of these constants as well as the statistical parameter R^2 are given in Table 2. The trend value (2.15 ppm/year) is the highest in Basra and the lowest (2.04 and 2.07 ppm/year) in Baghdad and Mosul. The excellent correlations ($R^2 = 0.997$ and 0.998) were found in the fitting lines. The slightly higher trend values in Basra and Baghdad (=2.26 and 2.21 ppm/year, respectively) were also found by AL-Shaban[31] for the period (2003–2022). These simple differences are to be expected due to the different time, although the data source is the same. The strongest trend is expected in Basra, as most of Iraq's oil production, manufacturing and cement industries are located to the south of Iraq.[32]

Spatial yearly means of $[CO_2]$ computed for overall Iraq with their low σ at each data point is plotted in Fig. 3. The linear straight through all points was passed using Eq. (4) with a trend value = 2.11 ppm/year and $\gamma = -3857.7$, as recorded in Table 2. Over the period considered, the increase in $[CO_2]$ is linear.

As shown in Fig. 3 above, the continuous increase in atmospheric $[CO_2]$ during the study period was largely due to human activities, mainly the burning of oil and natural gas during oil production and energy, transportation and land cover changes, and serious air contamination. This is also confirmed by yearly CO_2 emission rates for the period (2000–2021) from fossil fuel combustion and cement production[29] concerning Global Carbon Update 2021. The level of emissions in Iraq over the past twenty years is shown in Fig. 4. The yearly growth rate of CO_2 emissions has doubled from 70 Gt in the year 2000 to 150 Gt in the year 2021. The increased amount of CO_2 emissions (80 Gt) during this period, of course, enhances the existing CO_2 in the atmosphere rather than being removed by natural processes, so that the amount of $[CO_2]$ increases each year.[32] This can also be enhanced from the results published in these references that the highest production of natural gas was in 2013 with 21.4 billion.m^3/year, while natural gas flaring was 12.4 billion.m^3/year, where Iraq was the second largest source of gas flaring in the world.[32] Finally, Iraq shared 0.9% of global cumulative CO_2 emissions due to land use change during the period 2002–2026.[32]

Historical yearly variations of the SAT data in Iraqi provinces are plotted together in Fig. 5 for the period of (1971–2022). The selection of this period is for a more accurate estimation of the trend which is the most common and effective tool for predicting the

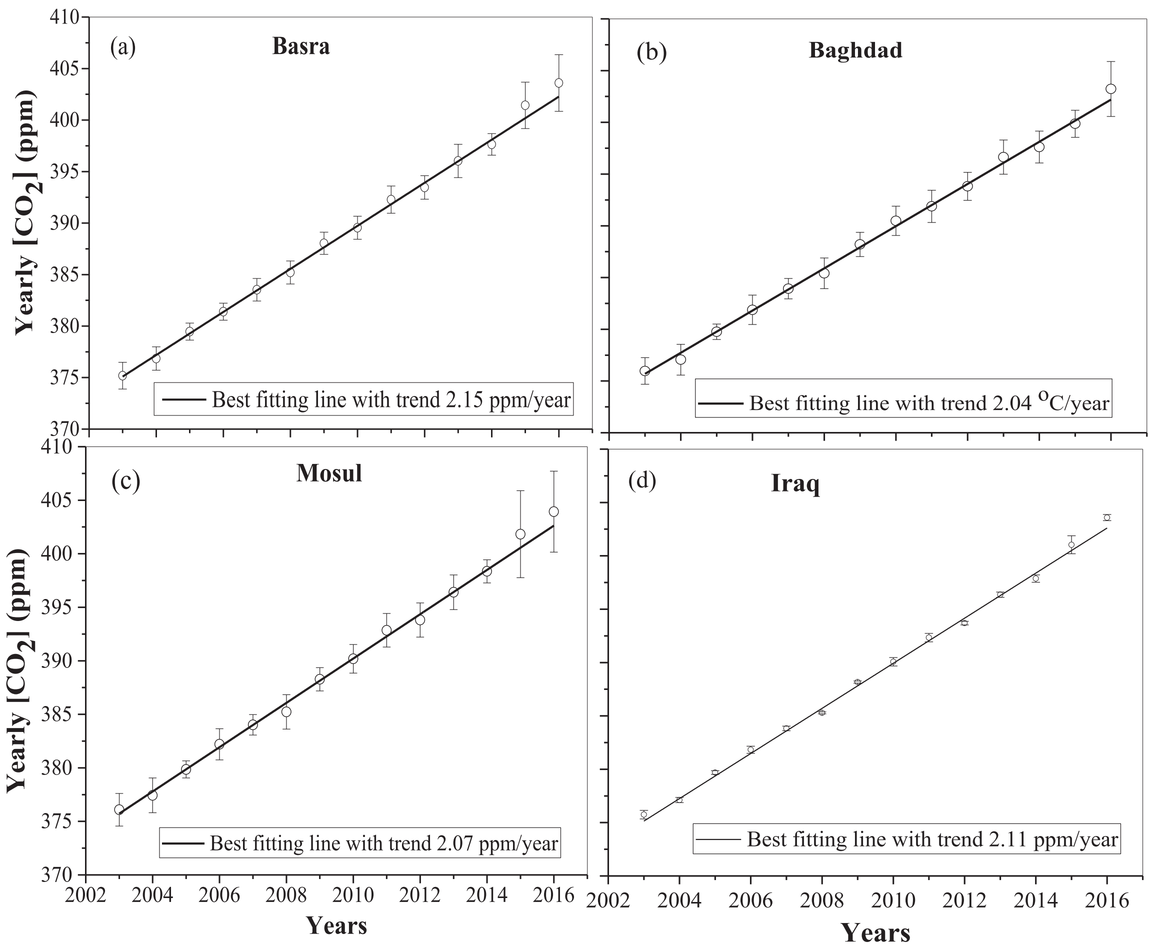

Fig. 3. Yearly variations of $[CO_2]$ in Basra (a), Baghdad (b), Mosul (c), and Iraq (d) from 2003 to 2016.

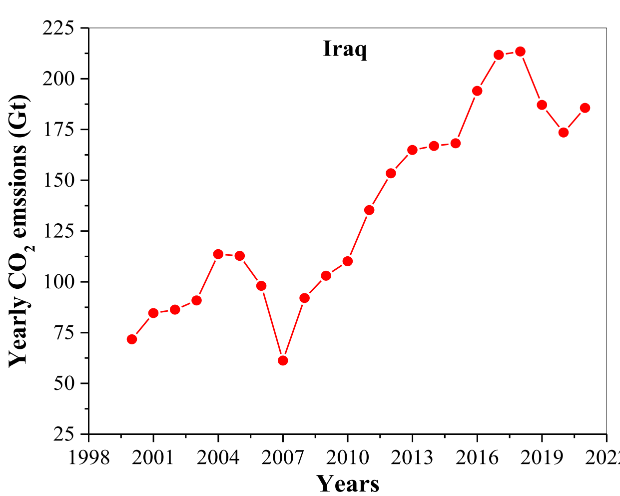

Fig. 4. Yearly CO_2 emission rate variation for Iraq, 2000–2021.[33]

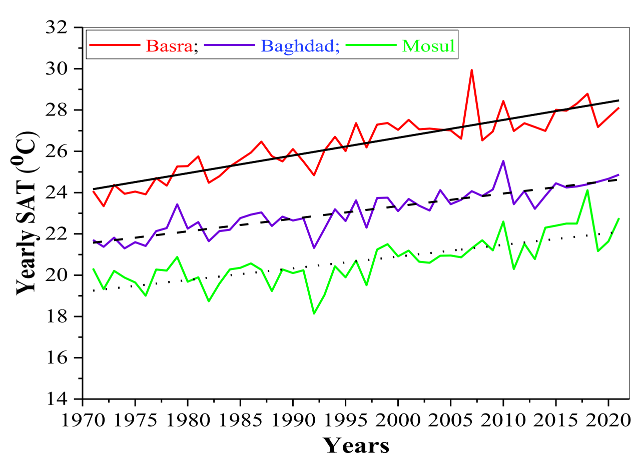

Fig. 5. Yearly variations in SAT of Basra, Baghdad and Mosul over the period (1971–2022).

increase in air temperature avoiding the variability over time. Additionally, to achieve the objectives of this study, the future estimates of CS levels over any time can be met. Although geographical location and elevation have a role to play in this distribution, there is an increased behavior in SAT in all cities, with an inclination from south to center to north.

The best fitting lines were drawn from Eq. (4) through the yearly SAT values with derived constants

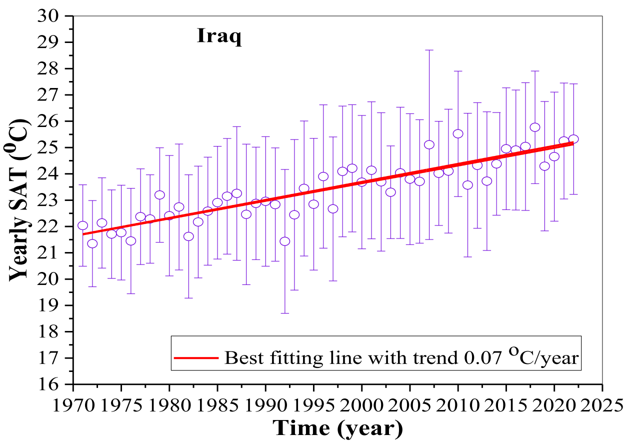

Fig. 6. Yearly variation of the spatial mean SAT from 1971 to 2022 in Iraq.

(i.e., γ and β) and R^2, which are also reported in Table 2 above. The province of Basra shows the highest positive trend (0.09 °C/year, red line), Baghdad less so (0.06 °C/year, blue line), and Mosul the lowest (0.048 °C/year, green line). For comparison with some previous studies conducted in the same provinces, using the Mann-Kendall test, Al-Timimi and Al-Khudhairy[34] found the same yearly upward trends for Baghdad and Mosul, but lower in Basra (0.07 °C/year) for the period (1980–2015), while Robaa and Al-Barazanji[35] found lower yearly upwards trends in all provinces: 0.05 (Basra), 0.015 (Baghdad), and 0.02 °C/year (Mosul) for the period (1941–2010). Basra's highest trend is due to low latitude and elevation (Table 1). It is also in the vicinity of bodies of water,[36] where there are features with large quantities of water vapor. Mosul, despite having a different latitude and surface type, had the same level of mean SAT and variation.[34]

Based on the above SAT data of each city between 1971 and 2022, the spatial yearly mean of SAT was calculated for the whole of Iraq. Fig. 6 displays SAT time series with its trend and the σ value at every point. The mean yearly trend is generally increasing with a value of 0.07 °C/year, which is larger than that found by Robaa and Al-Barazanji[35] and Al-Timimi and Al-Khudhairy[34] of 0.05 and 0.06 °C/year, respectively. The largest mean yearly trend observed in this study reflects that Iraq has experienced continuous warming. There is an interesting result that can be seen in Fig. 6 where the lower values of σ were found in the years before 1980 and then they were increased with the highest σ occurring in 2007. This means that the interannual variability was low before 1980 and then started to increase, so using the trend in this study has the advantage of reducing the random inter-annual variability.

Climate sensitivity estimation in Iraq

To assess CS under higher CO_2 levels, the typical short-term period of 20 years (2003–2022) should be completed according to the methodology of this paper. The value of the atmospheric [CO_2] in 2022 was extrapolated for all study areas using the linear regression Eq. (3). For Basra, Baghdad and Mosul, these yearly concentrations were 416.5, 416.08 and 415.6 ppm respectively, while For Iraq it was 408.7 ppm (Table 3). These results are consistent with the most recent records studied by AL-Shaban[31] for five GHGs including [CO_2] for the time (2003–2022) in five provinces including Basra and Baghdad. However, as shown in Table 3, the percentages of exceedances were calculated for all cities and Iraq using Eq. (5). The largest percentage was found in Basra with 10.8% and the least (10.5%) in Mosul, while the total value was 8.7% for Iraq. The local climatic warming will be negatively affected by these exceedances, making it difficult for sustainable development.

Considering the comparison between the spatial yearly SAT, ΔSAT, at the start and end of the given yearly interval from 2003 to 2022, we have chosen. This difference has been determined separately for each city and Iraq, which is illustrated in Table 4. Interestingly, positive ΔSAT values of 1.4, 1, and 0.75 °C were found in Baghdad, Basra, and Iraq, while negative ΔSAT (=–0.14 °C) was found in Mosul. The largest ΔSAT is to be expected, as there was a strong urban heat island effect in Baghdad.

The influence of the continuous increase of the spatial annual CO_2 concentration on the annual SAT is now examined. The relationship between the two

Table 2. Constant values in Eq. (4) of both [CO_2] for (2003–2016) and yearly mean SAT (1971–2022) with their R^2.

	Eq. (4) for [CO_2]			Eq. (4) for SAT		
Province	γ	β (ppm/year)	R^2	γ	β (°C/year)	R^2
Basra	–3930.8	2.15	0.997	–145.3	0.09	0.78
Baghdad	–3708.8	2.04	0.998	–98.8	0.061	0.76
Mosul	–3769.9	2.07	0.998	–96.6	0.057	0.55
Iraq	–3857.7	2.11	0.995	–110.5	0.067	0.83

Table 3. Estimates of $[CO_2]$ in 2022 and percentage increases over the 20 years.

Province	Basra	Baghdad	Mosul	Iraq
$[CO_2]$ in 2003 (ppm)	375.2	376.0	376.1	375.8
$[CO_2]$ in 2022 (ppm)	416.5	416.1	415.6	408.7
$\Delta[CO_2]$ (ppm)	41.3	40.1	39.5	33.0
Exceeding in $[CO_2]$ (%)	10.8	10.7	10.5	8.7

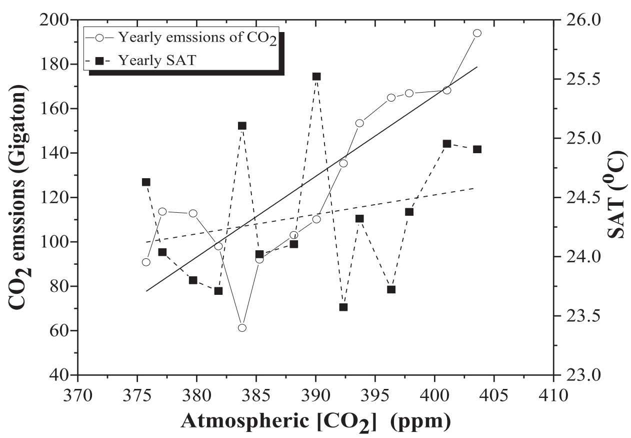

Fig. 7. Yearly $[CO_2]$ versus yearly CO_2 emission and SAT.

with SAT rising slightly as CO_2 levels increase is shown in Fig. 7, although the dispersion of the data is noticeable. A best-fit line was drawn through these data, satisfying Eq. (4) with $R^2 = 0.06$, where $\gamma = 17.9$ and $\beta = 0.016$ °C/ppm. This poor relationship with great variability was also explained. This is an indication that, at the regional scale, yearly temperature is a complicated result of local physical and artificial factors. Some of these were discussed in the introduction, and others may be due to alterations in station location, setting of many stations, and spatial scale. Similarly, the relation between yearly CO_2 emissions and $[CO_2]$ presented in Fig. 7 has a high correlation. The best line following Eq. (4) with $R^2 = 0.71$ is drawn through these data, that has a steep slope. The constants $\gamma = -1287.6$ and $\beta = 3.6$ Gt/ppm were found.

Now, the estimation of the CS of the increasing amounts of CO_2 gas released over Iraq is discussed below, while the TLCR was calculated by Eq. (2) for all sites studied over 20 years. The TLCR results are multiplied by a factor of 1.5 to obtain the ELCS estimates, based on Eq. (3). Table 4 shows all the TLCR and ELCS results. It is noticed that Iraq's capital had the highest TLCR (4.79 °C), while the lowest (–0.48 °C) was in Mosul, which is located at a highland (see Table 1) with lower CO_2, water vapor, and barometric pressure. This negative small value resulted from the fact that ΔSAT ($=SAT_{2022}–SAT_{2003}$) was negative in Mosul (see Fig. 5). Alternatively, this value also produced small values for TLCR and ELCS. This is expected for several reasons, while short- or medium-term climate variability could lead to periods of cooling or minimal warming in certain regions. The specific time could also influence the observed trends. If Mosul had experienced unusual warming in past decades due to temporary factors (e.g., extreme weather events, El Niño effects), more recent temperatures might show a slight decrease, resulting in a negative trend when comparing different periods. Mosul has not experienced significant urban expansion or modernization compared to other cities. Mosul's specific geography, topography, and land use may influence the local climate and limit warming compared to other areas. Factors such as the presence of rivers (the Tigris flows through Mosul), vegetation, and urbanization can alter temperature patterns. Each of these factors, or a combination of them, could be contributing to the limited warming observed in Mosul.

The overall assessment of the TLCR for Iraq is 2.55 °C. This is at the upper end of the range suggested in the IPCC literature review. Higher TLCRs and ELCSs provide insight into the short- to medium-term impacts of greenhouse gas emissions on climate, such as an increase in extreme maximum temperatures, more frequent droughts and water scarcity, rural-urban migration, public health crises and energy demand. For Iraq, the impact of a TLCR ceiling would be severe due to the region's pre-existing vulnerability to climate change. Therefore, policy makers need to take more action to avoid severe climate change, especially in Baghdad, while a lower value of TLCR and ELCS, as in Mosul, shows that it has more time to adapt. There are several practical suggestions to deal with the growing implications of the findings in this paper, such as preventing desertification, maintaining vegetation using new technologies, pushing negotiations with Turkey and Iran to recognize Iraq's rights to their shared waters, protecting and establishing oases in desert and arid areas, increasing public awareness and education on water conservation, building wastewater treatment systems in villages and rural areas outside urban centers, and improving energy efficiency by achieving zero gas flaring.

Iraq also needs to focus on both mitigation strategies (to reduce CO_2 emissions) and adaptation efforts (to cope with unavoidable climate changes). The most active proposals that can be implemented to reduce the risks of higher TLCR and ELCS are transitioning to renewable energy, improving energy efficiency, reducing dependence on oil and gas, and sustainable agricultural practices. The country's transition to renewable energy is an active and vital step.

Table 4. Estimates of the spatial mean yearly change in SAT, TLCR and ELCS over the last 20 years.

Cities	Basra	Baghdad	Mosul	Iraq
ΔSAT (°C)	1	1.4	–0.14	1.6
TLCR (°C)	3.34	4.79	–0.48	2.55
ELCS (°C)	5.01	7.18	–0.72	3.8

Furthermore, engaging the public and private sectors in these efforts, while fostering international cooperation, can help Iraq mitigate the worst impacts of climate change while promoting a sustainable future.

As stated in Table 4, the range of ELCS over Iraqi cities was (–0.72–7.18 °C) with a mean of 3.8 °C, within the range limited by IPCC 5th Assessment Report. The ELCS was 7.18 °C in Baghdad, suggesting that local warming will be difficult to achieve below 2 °C if atmospheric CO_2 concentrations continue to rise.[32]

From Eq. (2), the annual values of TLCR and C_1 and C_2 can be used to recalculate the linear proportional coefficient (=1/2*ΔSAT*log(2)) that varies with the forcing agent. The mean value for the whole of Iraq was 0.145. Such a small value implies that atmospheric CO_2 concentrations are only estimated globally. Thus, well-mixed CO_2 concentrations have a long lifetime in the atmosphere.

Conclusion

The response of SAT to ongoing human activities, especially to increasing atmospheric [CO_2], is the key to the interpretation of climate alteration in a particular region. Using the yearly averages for [CO_2] and its emission rate for the period (2003 to 2022) in three cities of Iraq, the yearly changes are analyzed to investigate the local climate response to the growing increase in the [CO_2] in the atmosphere, and then its effect on the change in SAT. The trends of 2.15, 2.04, 2.07 and 2.11 ppm/year for Basra, Baghdad, Mosul and Iraq, respectively, were calculated using the linear fitted regression equation to fit the CO_2 data. They have also been used to compensate for the lack in CO_2 data to complete the 20 years needed to evaluate the TLCR and ELCS. This is also dependent on the yearly mean changes in SAT over this period. The yearly relationship between CO_2 concentrations and mean SAT in Iraq was found to be slightly upward linear with a trend of 0.016 °C/ppm. TLCR and ELCS were highest in Baghdad and lowest in Mosul. Overall, their values in Iraq (2.55 and 3.8 °C) were at the upper end of the range recommended by the IPCC. The application of climate sensitivity to local and regional scales faces several significant limitations that arise from the inherent complexity of the climate system and the interplay of various factors, such as better local data and a more detailed representation of regional drivers.

By focusing on several research areas, such as improved representation of land use/cover change, long-term observations, focus on extreme events, regional downscaling of global climate models, and uncertainty analysis, future work on CS at regional scales can provide more precise and actionable insights to support better adaptation and mitigation efforts in different geographic areas.

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Authors' declaration

- Conflicts of Interest: None.
- We hereby confirm that all the Figures and Tables in the manuscript are ours. Furthermore, any Figures and images, that are not ours, have been included with the necessary permission for republication, which is attached to the manuscript.
- No animal studies are present in the manuscript.
- No human studies are present in the manuscript.
- Ethical Clearance: The project was approved by the local ethical committee at Mustansiriyah University.

Authors' contribution statement

D.A., L.M. and M.H. designed the study. L.M. and D.A. collected and analyzed the data statistically. M.H. and L.M. wrote the paper with input from all authors.

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تقييم حساسية المناخ لثاني أوكسيد الكربون الجوي في البصرة وبغداد والموصل: العراق

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المستخلص

يعاني العراق من ارتفاع مستمر في درجة حرارة الهواء السطحي (SAT)، مما يتسبب في تدهور عام في النظم البيئية. تم تقدير حساسية المناخ (CS) التي تشير إلى الزيادة في SAT التي يسببها ازدواجية تركيز ثاني أكسيد الكربون [CO_2]، من خلال الاستجابة المناخية المحلية العابرة (TLCR) والحساسية المناخية المحلية المتوازنة (ELCS). كما تم تحليل السلاسل الزمنية للمتوسطات السنوية المكانية لكل من [CO_2] ودرجات حرارة الهواء، واستخدم نموذج انحدار خطي لإيجاد اتجاهات سنوية لتركيز ثاني أكسيد الكربون و[CO_2]. استنادًا إلى البيانات التاريخية السنوية لتراكيز ثاني أكسيد الكربون (2003-2016)، وانبعاثات ثاني أكسيد الكربون (2000-2021) و(1971-2022 SAT)، تم تقييم CS لثلاث مناطق رئيسية في العراق: البصرة وبغداد والموصل والعراق بأكمله. أظهرت النتائج أن المتوسط السنوي لـ SAT و [CO_2] في العراق تم ملائمته بشكل جيد من خلال نموذج الانحدار بقيم ppm/year2.11 و0.07 ppm/year على التوالي. وعلى مستوى المحافظات المختارة، كانت أعلى اتجاهات تصاعدية في المتوسط التصاعدي للتحول إلى المناخ و[CO_2] في البصرة بقيم ppm/year2.15 و °C/year0.09 على التوالي، وذلك بسبب تضاعف انبعاثات ثاني أكسيد الكربون من 70 في عام 2000 إلى Gt150 في عام 2021. وتظهر النتيجة أيضاً أن قيمتي TLCR وELCS في العراق هي 2.55 و3.8 درجة مئوية على التوالي، والتي تبين أنها ضمن النطاق المقترح في تقرير التقييم الخامس للفريق الحكومي الدولي المعني بتغير المناخ بالنسبة للعراق.

الكلمات المفتاحية: حساسية المناخ، نزعة المناخ، تركيز [CO_2]، معدل الانبعاث لـ CO_2، درجة حرارة الهواء السطحية.