Article

Impact of carbon dioxide emissions caused by human activities on atmospheric temperature: A mathematical model

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Abstract
Various human activities have increased the concentration of carbon dioxide in the atmosphere leading to increase in average atmospheric temperature causing global warming. It threatens our environment as well as health and basic needs of human beings. Therefore, in this paper, a mathematical model is developed to study the effects of carbon dioxide emissions caused by human activities on average atmospheric temperature contributing global warming considering four dependent variables namely, the density of human population, cumulative density of human activities such as industries, automobiles, and power plants etc., the concentration of carbon dioxide and the average atmospheric temperature. The model is analyzed using stability theory of ordinary differential equations. Local and global stability conditions are established to study the feasibility of the model system. The growth rate of average atmospheric temperature is assumed to be proportional to the increased level of carbon dioxide concentration in the atmosphere from its equilibrium value. It is also assumed that this temperature decreases with a rate proportional to its enhanced level from its equilibrium value caused by various natural factors such as rain fall, snow fall, etc. The analysis shows that as the emission of carbon dioxide from human activities increases the average atmospheric temperature increases considerably from its equilibrium level.

Keywords mathematical model; carbon dioxide; average atmospheric temperature; stability analysis.

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1 Introduction

Rise in average atmospheric temperature is one of the most challenging problem caused by the greenhouse gases such as carbon dioxide, methane, etc., which are produced by various human activities in the form of industries, automobiles, and power plants (run by using coal) etc. (Afonso, 2020; Andrew, 2018; EPA, 2014; Ferrarini, 2012; Rai and Rai, 2013a, b; Singh and Sharma, 2012; Wu and Zhang, 2012; Tsai, 2019; Zhang and

Liu, 2012; Zhang and Zhang, 2012). Automobile, one of most important human activity related factor, is a major contributor to greenhouse gases in India. In present scenario, increasing demand and excessive use of automobiles have increased the level of carbon dioxide emission in the environment. As the concentration of a carbon dioxide reaches beyond its threshold level, it starts to harm our environment in different ways leading to rise in average atmospheric temperature. Threshold level of carbon dioxide is the level below which no visible harmful effects are observed (Engr and Thomas, 2015; Opare, 2016; Shaw, 2015; Sundar and Naresh, 2015). Coal is the largest source of thermal energy on earth used as fuel for thermal power plants producing electricity. Approximately 60% of electricity generation in our country is met by thermal power plants (Mishra, 2004). Deforestation is another main cause of rise in average atmospheric temperature. Deforestation is mainly caused by construction of roads, houses, use of land for agriculture, etc. which increases as population increase. Other reasons behind the deforestation are the increase in industrialization, which are also linked to human population (Agarwal and Pathak, 2015; Dubey and Narayanan, 2010; Lata et al., 2016; Naresh et al., 2006).

It has been observed that the average temperature of earth's surface increased from 0.6 to 0.9 degree Celsius during the last century. Due to this increase in average atmospheric temperature many adverse effects have been observed in the form of melting of glaciers, sea level rise, loss of biodiversity, drought, etc., (Ramanathan and Feng, 2009). Human activities are changing the carbon cycle both by adding more CO_2 to the atmosphere and by reducing the ability of natural sinks such as forests caused by deforestation to remove CO_2 from the atmosphere (Budzik, 2012; Millstein and Harley, 2009; Schneising et al., 2013). The overgrowth in population has also negative effect on the wildlife species (Adebayo, 2009).

Several investigations have been made to study the effect of industrialization on forestry resources using mathematical models, (Agarwal et al., 2010; Dubey et al., 2003; Dubey et al., 2009; Misra and Verma, 2013; Shukla et al., 2009; Vivi et al., 2015). For example, a mathematical is proposed and analyzed to study the effect of industrialization pressure on the ddepletion of forestry biomass (Agarwal et al., 2010). Misra and Verma (Misra and Verma, 2013) have studied the dynamics of carbon dioxide in the atmosphere using a nonlinear mathematical model.

In view of the above, in this paper, we have modeled and analyzed the effect of carbon dioxide emission caused by human activities on average atmospheric temperature leading to global warming.

2 Model

To model the phenomenon, we have assumed a regional atmosphere under consideration where the environment is affected due to emission of carbon dioxide caused by human activities. The following assumptions are made in the modeling process,

(i) The human population density $N(t)$ follows logistic model with growth rate r and carrying capacity K.

(ii) The growth rate of cumulative density of human activities related factors $A(t)$ is proportional to the human population $N(t)$ and it decreases in proportional to $A(t)$ caused by inefficiency of these factors.

(iii) The concentration $C(t)$ of carbon dioxide in the atmosphere increases with natural factors with constant rate Q as well as with cumulative density of human activities $A(t)$ with growth rate δ.

(iv) The average atmospheric temperature $T(t)$ above its equilibrium T_0 is proportional to the increased level of carbon dioxide (i.e. $C - C_o$) in the atmosphere.

In view of the above assumptions and considerations, the system is assumed to be governed by the following differential equations,

$$\frac{dN}{dt} = r\left(1 - \frac{N}{K}\right)N - r_0(T - T_0)N \tag{1}$$

$$\frac{dA}{dt} = \lambda N - \mu A \tag{2}$$

$$\frac{dC}{dt} = Q + \delta A - \delta_0 C \tag{3}$$

$$\frac{dT}{dt} = \theta(C - C_0) - \theta_0(T - T_0) \tag{4}$$

$$N(0) \geq 0,\ A(0) \geq 0, C(0) = C_0 \geq 0, T(0) = T_0 \geq 0$$

Since the growth of population is affected adversely by the average atmospheric temperature contributing global warming significantly, the decrease in population density is taken to be in direct proportion to $(T - T_0)$ as well as to the population density (i.e. the death increases due to global warming). The constant r_0 is the death rate coefficient of population density due to average atmospheric temperature. The constant λ is the growth rate coefficient of cumulative density $A(t)$ of human activities related factors as discussed above and μ is its depletion rate coefficient due to natural factors such as the inefficiency of these factors. The carbon dioxide is emitted in to the atmosphere from various natural sources as well as human activities related factors. Let Q be the constant input of carbon dioxide from natural sources and δ is its growth rate coefficient due to human activities related factors as discussed above. The constant δ_0 represents natural depletion rate coefficient of carbon dioxide. Further, the presence of greenhouse gases in excess in the atmosphere lead to increase in average atmospheric temperature contributing global warming. Since, carbon dioxide is a potent greenhouse gas therefore it will increase average atmospheric temperature significantly when the concentration of carbon dioxide crosses its threshold level. This increase in average atmospheric temperature in assumed to be proportional to $C - C_o$ where C_o is the threshold concentration of carbon dioxide. The constant θ is the growth rate coefficient of temperature T with its natural depletion rate coefficient θ_0. The model implies that $C = C_o$ when $T = T_0$.

Remark 1. It is noted from equation (1) that $r - r_0(T - T_0)$ is the growth rate of human population and it is positive for the feasibility of the model system (1) – (4). Therefore, $r - r_0(T - T_0) > 0$ for all time $t > 0$.

3 Equilibrium Analysis

The model (1) – (4) has the following two equilibria,

(1) $E_0(0,0,C_0,T_0)$

(2) $E^*(N^*, A^*, C^*, T^*)$

The existence of equilibria E_0 is obvious.

The existence and uniqueness of nontrivial equilibrium E^* is carried out as follows.

The solution of different variables in $E^*(N^*, A^*, C^*, T^*)$ is given by the following algebraic equations,

$$N = \frac{K}{r}\{r - r_0(T - T_0)\} \tag{5}$$

$$A = \frac{\lambda}{\mu} N \tag{6}$$

$$Q + \delta A - \delta_0 C = 0 \tag{7}$$

$$T = T_0 + \frac{\theta}{\theta_0}(C - C_0) \tag{8}$$

Using equation (8) in equation (5), we get

$$N = \frac{K}{r}\left\{r - r_0 \frac{\theta}{\theta_0}(C - C_0)\right\} \tag{9}$$

Using equations (6) and (9) in equation (7) we can defined a function $F(C)$ as follows,

$$F(C) = Q + \frac{\delta\lambda K}{\mu r}\left\{r - r_0 \frac{\theta}{\theta_0}(C - C_0)\right\} - \delta_0 C = 0 \tag{10}$$

From equation (10), we note that,

(i) $F(C_0) = \dfrac{\delta \lambda K}{\mu} > 0$

(ii) $F(C_m) = -\left(\dfrac{\delta\lambda K}{\mu}\right)^2 \left(\dfrac{r_0\theta}{\delta_0 r \theta_0}\right) < 0$ (11)

(iii) $F'(C) = -\delta_0 - \dfrac{\delta\lambda r_0 \theta K}{\mu r \theta_0} < 0$

Thus, $F(C) = 0$ has a unique root (let $C = C^*$) in $C_0 < C < C_m$ within the region of attraction Ω.

Knowing the value of $C = C^*$, the positive values of N^*, A^* and T^* can be obtained from equations (5), (6) and (8) respectively.

It can easily be noted from equation (10) that,

$$\frac{dC}{d\lambda} = \frac{\dfrac{K\delta}{\mu r}\left\{r - r_0 \dfrac{\theta}{\theta_0}(C - C_0)\right\}}{\delta_0 + \dfrac{\delta\lambda r_0 \theta K}{\mu r \theta_0}} > 0, \text{ as } C > C_0$$

This implies that C increases as λ increases. Similarly, we can show easily that $\dfrac{dN}{d\theta} < 0$, $\dfrac{dT}{d\lambda} > 0$ and $\dfrac{dT}{d\delta} > 0$.

4 Stability Analysis

The local stability of the equilibria can be investigated by determining the sign of the eigenvalues of Jacobian matrix evaluated at each equilibria. The Jacobian matrix for the model system (1) - (4) is given as follows:

$$J = \begin{bmatrix} r\left(1 - \dfrac{2N}{K}\right) - r_0(T - T_0) & 0 & 0 & -r_0 N \\ \lambda & -\mu & 0 & 0 \\ 0 & \delta & -\delta_0 & 0 \\ 0 & 0 & \theta & -\theta_0 \end{bmatrix}$$

It can easily be checked that $E_0(0,0,C_0,T_0)$ is unstable as one eigenvalue is positive.

Now we proceed to determine the local stability of E^*

Theorem 1 The equilibrium E_0 is unstable but the equilibrium E^* is locally asymptotically stable provided the following condition is satisfied in the neighborhood of E^*.

$$r_0 K \lambda \delta \theta < r \theta_0 \mu \delta_0 \tag{12}$$

Proof. To check the local stability of $E^*(N^*, A^*, C^*, T^*)$, we consider the following positive definite function,

$$U = \frac{1}{2}k_1 N_1{}^2 + \frac{1}{2}k_2 A_1{}^2 + \frac{1}{2}k_3 C_1{}^2 + \frac{1}{2}k_4 T_1{}^2 \tag{13}$$

where $N_1 = N - N^*$, $A_1 = A - A^*$, $C_1 = C - C^*$ and $T_1 = T - T^*$, where k_1, k_2, k_3, k_4 are positive constants chosen suitably.

Differentiating above equation with respect to $'t'$ we get

$$\frac{dU}{dt} = k_1 N_1 \frac{dN_1}{dt} + k_2 A_1 \frac{dA_1}{dt} + k_3 C_1 \frac{dC_1}{dt} + k_4 T_1 \frac{dT_1}{dt}$$

Putting the values of the linearized form of derivatives and simplifying, we get,

$$\frac{dU}{dt} = -k_1 \frac{r}{K} N^* N_1^{\ 2} - k_2 \mu A_1^{\ 2} - k_3 \delta_0 C_1^{\ 2} - k_4 \theta_0 T_1^{\ 2} + k_2 \lambda N_1 A_1 - k_1 r_0 N^* N_1 T_1$$

$$+ k_3 \delta A_1 C_1 + k_4 \theta C_1 T_1 \tag{14}$$

After some algebraic manipulations and by choosing,

$$k_1 = 1, k_2 < \frac{r\mu N^*}{\lambda^2 K}, \quad k_3 < \frac{r\mu^2 \delta_0 N^*}{\lambda^2 \delta^2 K}, \quad \frac{r_0^{\ 2} K N^*}{r\theta_0} < k_4 < \frac{r\theta_0 \mu^2 \delta_0^{\ 2} N^*}{\lambda^2 \delta^2 \theta^2 K}$$

$\frac{dU}{dt}$ will be negative definite and hence E^* is locally asymptotically stable provided the condition (12) is satisfied.

To establish the nonlinear stability character of E^*, we need bounds of dependent variables involved. For this, we state the region of attraction in the form of following lemma.

Lemma 1

The set $\Omega = \left\{ (N, A, C, T) \in R_+^4 : 0 \le N \le K, 0 \le A \le \frac{\lambda K}{\mu}, C_0 < C \le C_m, T_0 \le T \le T_m \right\}$, where $C_m = \frac{\delta \lambda K}{\delta_0 \mu} + C_0$ and $T_m = \frac{\theta}{\theta_0}(C_m - C_0) + T_0$, attracts all solutions initiating in the interior of positive octant.

Proof. From equation (1),

$$\frac{dN}{dt} \le r\left(1 - \frac{N}{K}\right) N$$

From which we get $\underset{t\to\infty}{Lim} \sup N(t) = K$

Again from equations (2) we have,

$$\frac{dA}{dt} = \lambda N - \mu A$$

$$\le \lambda K - \mu A$$

Using comparison theorem, it can be seen that,

$$\underset{t\to\infty}{Lim} \sup A(t) = \frac{\lambda K}{\mu}$$

Similarly from equation (3) and (4) we can show that,

$\underset{t\to\infty}{Lim} \sup C(t) = C_m$ and $\underset{t\to\infty}{Lim} \sup T(t) = T_0 + \frac{\theta}{\theta_0}(C_m - C_0)$ respectively, where $C_m = \frac{\delta \lambda K}{\delta_0 \mu} + C_0$.

Hence the proof.

Theorem 2 The equilibrium E^* is globally asymptotically stable provided the following condition is satisfied inside the region of attraction Ω,

$$S = r\theta_0\mu\delta_0 - r_0K\lambda\delta\theta > 0 \tag{15}$$

Proof: To establish nonlinear stability behavior of E^*, the following positive definite function is considered,

$$V = m_1\left(N - N^* - N^*\log\frac{N}{N^*}\right) + \frac{1}{2}m_2(A - A^*)^2 + \frac{1}{2}m_3(C - C^*)^2 + \frac{1}{2}m_4(T - T^*)^2 \tag{16}$$

Differentiating with respect to 't' yields,

$$\frac{dV}{dt} = m_1(N - N^*)\frac{1}{N}\frac{dN}{dt} + m_2(A - A^*)\frac{dA}{dt} + m_3(C - C^*)\frac{dC}{dt} + m_4(T - T^*)\frac{dT}{dt}$$

Using the model equations it is simplified to,

$$\begin{aligned}\frac{dV}{dt} = &-m_1\frac{r}{K}(N - N^*)^2 - m_2\mu(A - A^*)^2 - m_3\delta_0(C - C^*)^2 - m_4\theta_0(T - T^*)^2 \\ &+ m_2\lambda(N - N^*)(A - A^*) - m_1r_0(N - N^*)(T - T^*) \\ &+ m_3\delta(A - A^*)(C - C^*) + m_4\theta(C - C^*)(T - T^*)\end{aligned} \tag{17}$$

After some algebraic manipulations and by choosing,

$$m_1 = 1, m_2 < \frac{r\mu}{\lambda^2K}, \quad m_3 < \frac{r\mu^2\delta_0}{\lambda^2\delta^2K}, \quad \frac{r_0{}^2K}{r\theta_0} < m_4 < \frac{r\theta_0\mu^2\delta_0{}^2}{\lambda^2\delta^2\theta^2K}$$

$\frac{dV}{dt}$ is negative definite and hence E^* is globally asymptotically stable, provided the condition (15) is satisfied inside the region of attraction Ω.

Remark 2. Above theorems imply that as the parameters λ, δ or θ approaches to zero the possibility of satisfying these conditions is more plausible. This implies that these parameters have destabilizing effect on the model system.

5 Numerical Simulations

In this section, numerical simulation is performed to check the feasibility of analytical results for the model system (1) – (4) by taking into account the following set of parameter values,

$$Q = 100, r = 0.5, K = 1000, r_0 = 0.005, C_0 = 100, T_0 = 13.5, \lambda = 0.04, \mu = 0.03, \delta_0 = 0.3$$

$$\delta = 0.02, \theta = 0.0002, \theta_0 = 0.04$$

The equilibrium values corresponding to different variables in E^* so obtained are

$N^* = 983.9601765, A^* = 1311.946902, C^* = 420.7964601, T^* = 15.10398230$.

The eigenvalues of the Jacobian matrix J corresponding to equilibrium point E^* are $-0.49196, -0.030679, -0.039281$ and -0.30005. Since all the eigenvalues are negative and hence equilibrium E^* is locally asymptotically stable. For the given parameter values, nonlinear stability condition (15), corresponding to E^*, is also satisfied. To present nonlinear stability of E^* for the model system (1) – (4) in $N-A-C$ plane, trajectories with different initial starts have been plotted in $N-A-C$ plane as shown in Fig. 1. It is apparent from Fig. 1 that all trajectories approach the equilibrium E^* showing that the equilibrium E^* is nonlinearly stable.

To comprehend the variation of model variables with time for different values of crucial parameters these variables are plotted with time as shown in Figs 2-6. In Fig. 2, the variation of concentration of carbon dioxide with time 't' is shown for different values of growth rate coefficient of cumulative density of human activities related factors (i.e. λ). From this figure, it is noted that the concentration of carbon dioxide increases as the growth rate coefficient of cumulative density of human activities related factors increases.

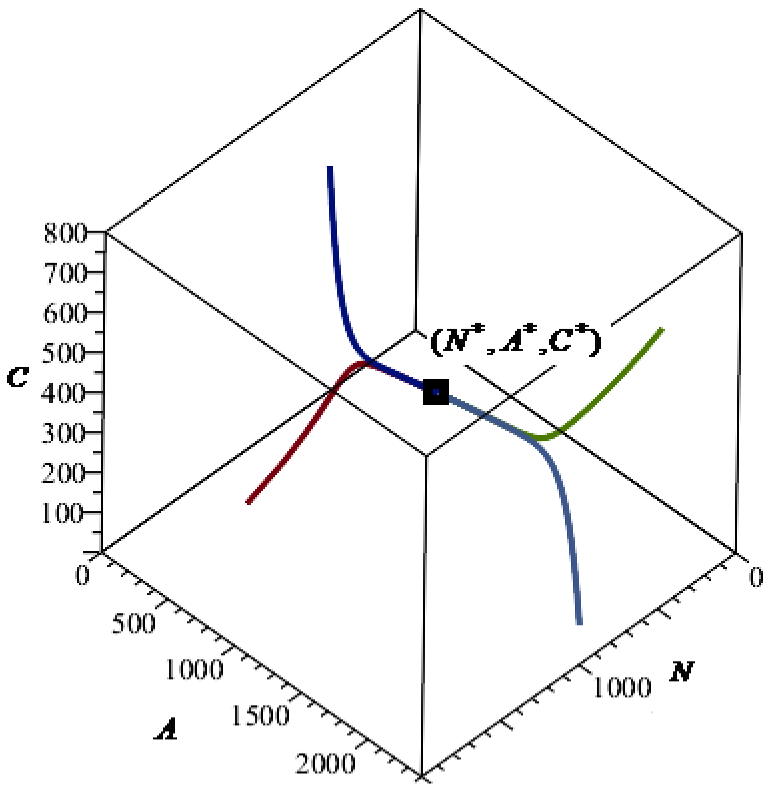

Fig. 1 Nonlinear stability in $N-A-C$ plane.

In Figs 3 and 4, the variation of the concentration of carbon dioxide (C) and the average atmospheric temperature (T) with time 't' is shown for different values of δ, the growth rate coefficient of carbon dioxide concentration due to human activities related factors. From these figures, it is observed that the concentration of carbon dioxide (C) and the average atmospheric temperature (T) increase with increase in the growth rate coefficient of carbon dioxide concentration due to cumulative density of human activities related factors. This elevated level of carbon dioxide has significant effect on global warming. In Fig. 5, the variation of human activities with time 't' is shown for different values of growth rate coefficient of cumulative density of human activities related factors (i.e. λ). From this figure, it is seen that the cumulative density of human activities related factors increases as the growth rate coefficient λ increases. In Fig. 6, the variation of density of human population with time 't' is shown for different values of the growth rate coefficient of the average atmospheric temperature (i.e. θ). From this figure, it is observed that the density of human population decreases as the growth rate coefficient of the average atmospheric temperature increases.

Stability condition has also been plotted with respect to crucial parameters to study the effect of these variables on stability condition. In Figs 7 and 8, the variation of nonlinear stability condition S with parameters δ and θ respectively is shown. It is apparent from Fig. 7 that S remains positive for $\delta < 4.5$, it becomes zero at $\delta = 4.5$ and negative for $\delta > 4.5$. This implies that the stability condition is satisfied for $0 \le \delta < 4.5$ and for higher values of δ it will not be satisfied. Hence, δ has destabilizing effect on the model system. Likewise, from Fig. 8 we depict that θ has destabilizing effect on the model system.

In Table 1, it is shown that the concentration of carbon dioxide and average atmospheric temperature increases as the growth rate coefficient of cumulative density of human activities related factors in the form of automobiles, industries and power plants etc. (i.e. λ) increases. In Table 2, it is shown that the concentration of carbon dioxide and average atmospheric temperature in the atmosphere increases as the growth rate coefficient of carbon dioxide concentration (i.e. δ) increases.

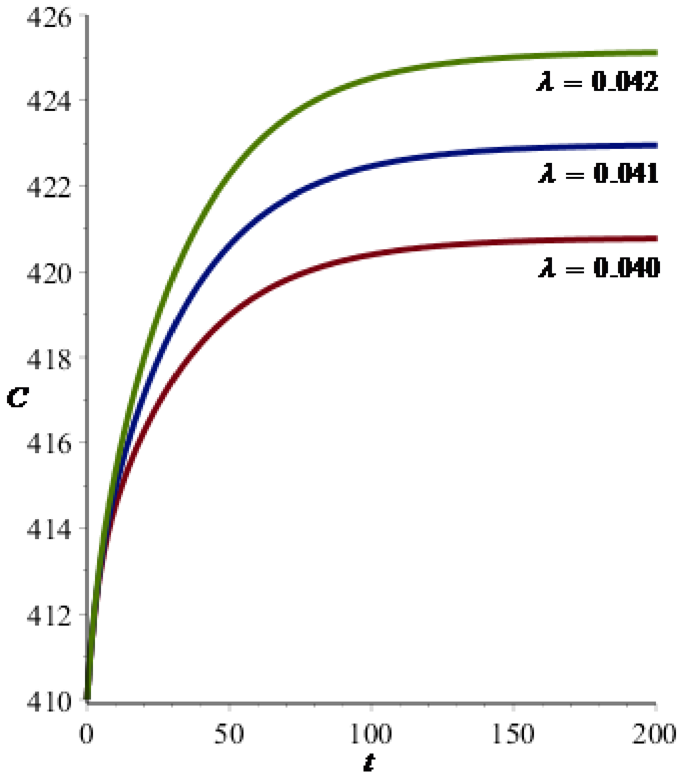

Fig. 2 Variation of C with time t for different values λ

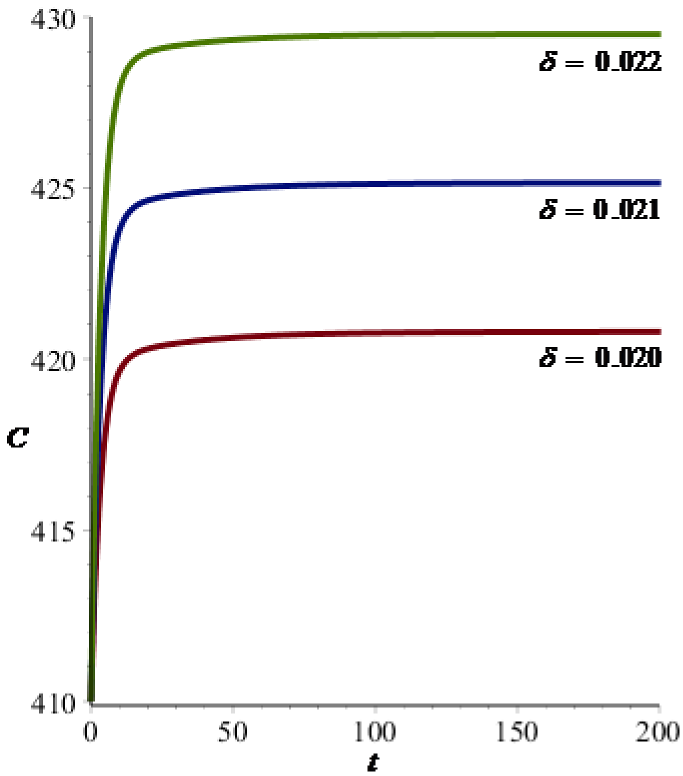

Fig. 3 Variation of C with time t for different values δ

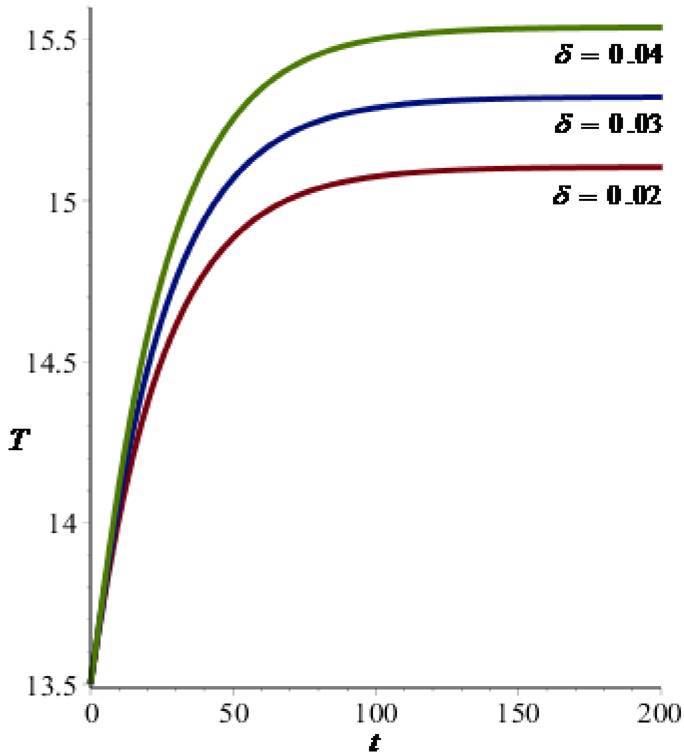

Fig. 4 Variation of T with t for different values of δ

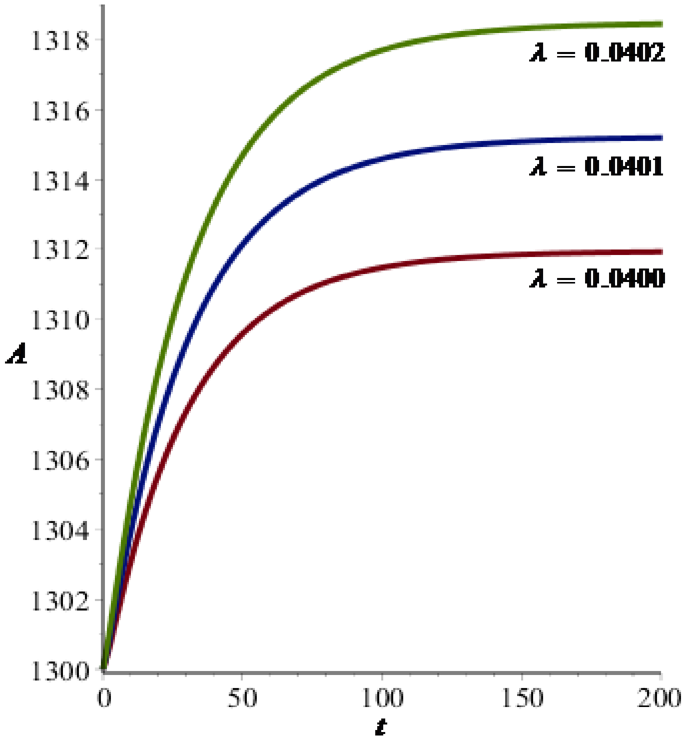

Fig. 5 Variation of A with time t for different values of λ

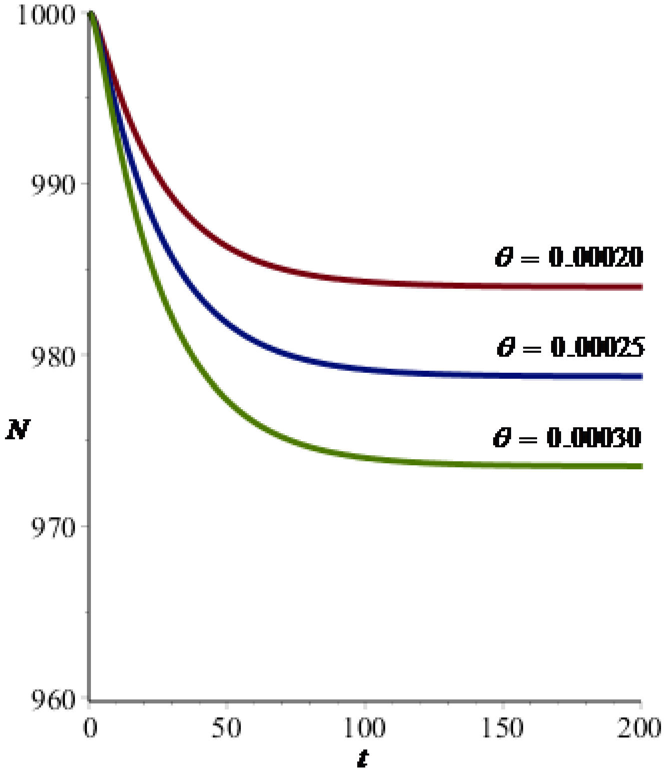

Fig. 6 Variation of N with time t for different values of θ

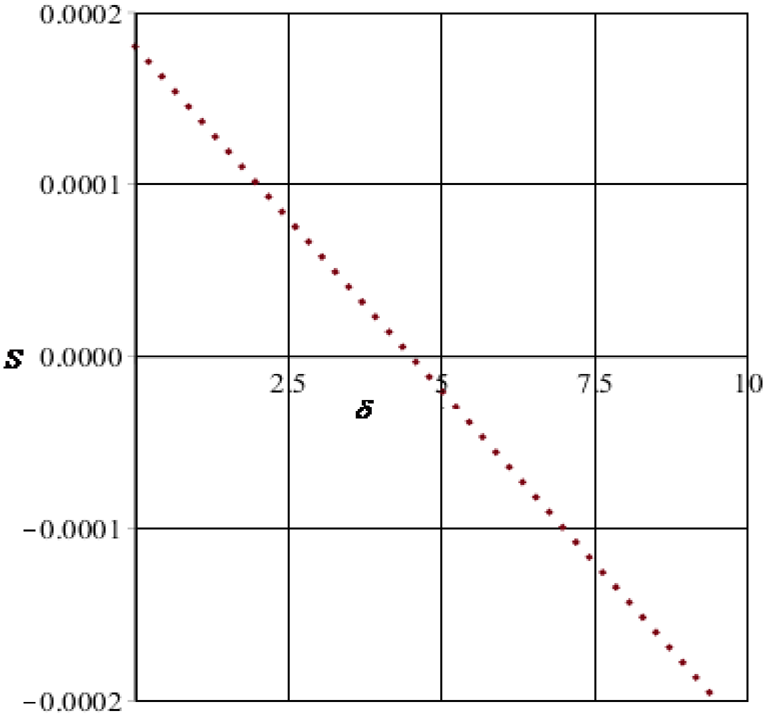

Fig. 7 Variation of stability condition S with δ

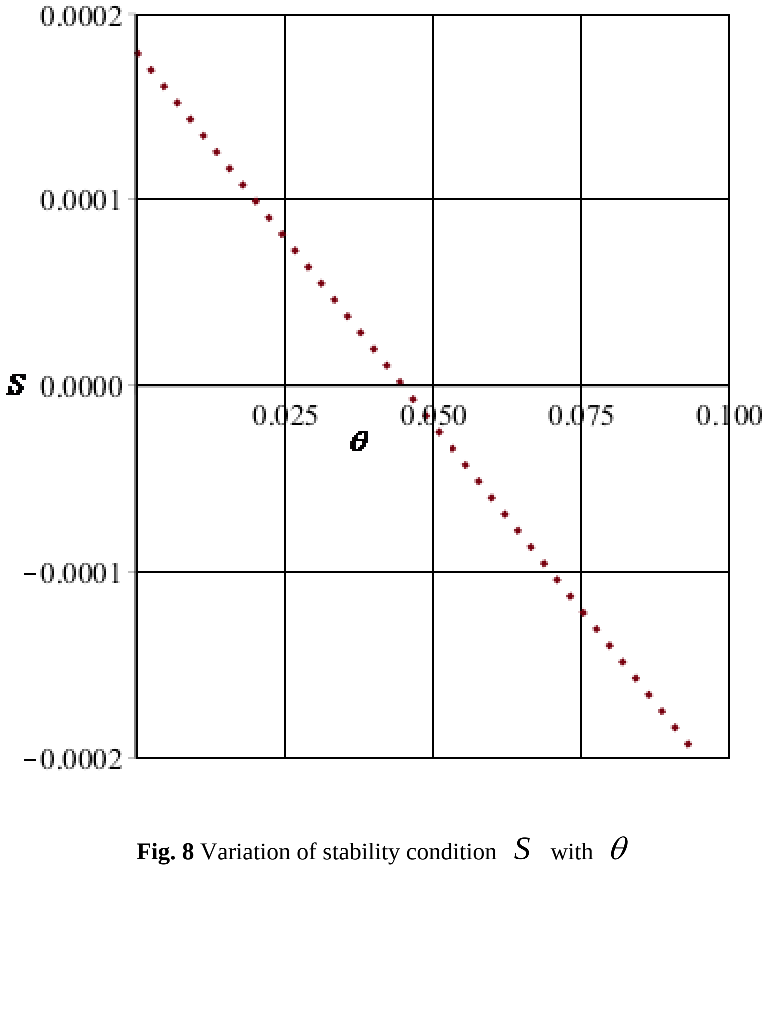

Fig. 8 Variation of stability condition S with θ

Table 1 Variation of C and T with λ

λ	0.038	0.039	0.040	0.041	0.042
C	416.4416906	418.6193163	420.7964601	422.9731224	425.1493032
T	15.08220845	15.09309658	15.10398230	15.11486561	15.12574652

Table 2 Variation of C and T with δ

δ	0.018	0.019	0.020	0.021	0.022
C	412.0849933	416.4416906	420.7964601	425.1493032	429.5002211
T	15.06042497	15.08220845	15.10398230	15.12574652	15.14750111

6 Conclusion

In this paper, an attempt has been made to comprehend the effect of CO_2 emission caused by human activities related factors such as automobiles, use of coal for running of industries and power plants etc., average atmospheric temperature leading to increase in global warming. The mathematical model under consideration has been assumed to be governed by a system of ordinary differential equations with four nonlinearly dependent variables namely, the density of human population $N(t)$, cumulative density of human activities related factors in the form of automobiles, industries and power plants etc. $A(t)$, the concentration of carbon dioxide $C(t)$ and the average atmospheric temperature $T(t)$. To model the phenomenon, it is assumed that the cumulative density of human activities related factors is proportional to the human population density. The growth rate of density of human population has been assumed to be governed by logistic model with their respective growth rate and carrying capacity. The concentration of CO_2 is considered to be proportional to the human activities related factors. The increase in the average atmospheric temperature has been assumed to be proportional to the increased level of concentration of CO_2 in the atmosphere from its threshold level.

The proposed model has been analyzed by using stability theory of ordinary differential equations and numerical simulations. It has been shown, analytically and numerically, that

(i) As the cumulative density of human activities related factors increases the concentration of CO_2 increases.

(ii) As the concentration of CO_2 increases the average atmospheric temperature increases.

(iii) As cumulative density of human activity related factors increases, the average atmospheric temperature increases as the concentration of CO_2 increases.

(iv) As average atmospheric temperature increases the population density decreases as its death rate increases.

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