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INVESTIGATING THE ROLE OF CHAOS THEORY IN UNDERSTANDING AND MITIGATING THE IMPACTS OF CLIMATE CHANGE

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ABSTRACT

Climate change is a complex and multifaceted phenomenon that affects the physical, biological, and social systems of the planet. As the global climate system is highly nonlinear and characterized by complex feedback loops and interactions, understanding the dynamics of climate change requires a comprehensive framework that can capture its inherent complexity. In recent years, the application of chaos theory to climate science has gained traction as a promising approach to understanding the chaotic behavior of the climate system. This research aims to investigate the role of chaos theory in understanding and mitigating the impacts of climate change. It will review the current state of the literature on chaos theory and climate science, with a focus on identifying key research gaps and areas for future research. Specifically, the study will explore how chaos theory can be used to model and predict the behavior of the climate system, and how it can inform the development of effective mitigation and adaptation strategies. The research will employ a mixed-methods approach, combining both quantitative and qualitative methods to analyze climate data, conduct simulations, and gather expert opinions. The result of this study provides better understanding of the complex dynamics of climate change, and inform policy decisions aimed at mitigating its impacts.

Keywords: Climate Change, Chaos Theory, Complexity, Mitigation, Adaptation

INTRODUCTION

Climate change is one of the most pressing issues facing humanity today, and its impacts are felt across the planet. As the Earth's climate system is highly complex and nonlinear, traditional linear models may not adequately capture its inherent complexity. In recent years, the application of chaos theory to climate science has emerged as a promising approach for understanding the chaotic behavior of the climate system (Morupisi, 2020). Unfortunately, the concept of chaos is poorly understood within most business, social science, and military literature and casual vernacular. The confusion is generated by the failure to distinguish between stochastic randomness and mathematical determinism (Fuqua, 2009).

Chaos theory is a branch of mathematics that deals with the behavior of nonlinear systems that are highly sensitive to initial conditions. The theory posits that small changes in the initial conditions of a system can lead to significantly different outcomes over time. This sensitivity to initial conditions, commonly referred to as the" butterfly effect," is a hallmark of chaotic systems. Chaos theory suggests disorder and unpredictability, which is partially correct, but does not represent the other vital aspect of chaotic systems - that they are deterministic, with changes occurring only within prescribed borders. Their unpredictability arises because minuscule changes in the starting conditions of Ross et al (2013). Mitigating impacts of climate change in stream food webs. chaotic system can produce widely different outcomes (Dalgleish, 1999). Chaos is random-like behavior with certain necessary but not sufficient criteria. In order to be considered chaos, a system must be bounded, nonlinear, sensitive to small changes in the initial conditions, and dynamical. Those ingredients do not guarantee chaos, but give the basic components that allow a deterministic system to be driven into random-like behavior (Ross et al., 2013).

Climate change is a prime example of a chaotic system. The earth's climate system is characterized by complex feedback loops and interactions between the atmosphere, oceans, land surface, and ice sheets. Small changes in one part of the system can have far-reaching impacts on other parts of the system, making it difficult to predict its behavior over longtime scales. Amore familiar example of chaotic system in climate change is the problem of weather forecasting. Very small changes in initial conditions can produce significant changes in the weather, even in the short to medium term, making forecasting extremely difficult. This is evident in the work of Lorenz, who tried to solve this problem during WWII so that the weather could be more accurately predicted for air-force sorties. Working with a simple computer, he realized that repeated equations in which several decimal places were rounded up (e.g.2.978658 becomes 2.97866) gave different results, leading to the conclusion that small changes in the initial conditions can lead to highly diverse outcomes.

Chaos theory provides a framework for understanding the complex and uncertain dynamics of the climate system (Kiel, 2006). The theory has been applied to different chaotic systems including: Military decision making, stock market, garment industry and fashion design, in human body and other areas (Biswas et al. 2018). By modeling the behavior of the system using chaotic models, researchers can gain insight into the underlying dynamics of climate change and identify potential tipping points and feedback loops that could have significant impacts on the global climate system. The purpose of this paper is to investigate the role of chaos theory in understanding and mitigating the impacts of climate change.

The Theory of Chaos of Dynamical Systems

The theory of Chaos can be modeled using a simple nonlinear difference equation, either with one-variable or multi-variable.

A one-variable chaos can be illustrated by the difference equation (1), where the next value of *x*, is generated from the previous value by a certain operation.

$$x_{i+1} = 9 - x_i^2 \qquad (1)$$

Based on equation (1), we can ascertain the sensitivity dependence upon initial conditions which will enhance the understanding of time paths that are random in nature. To simulate this system, a choice of an initial condition x_0= 0.5 and x = 1.0 are used. The graph of the system with these initial conditions are shown in figures 1 and 2 respectively.

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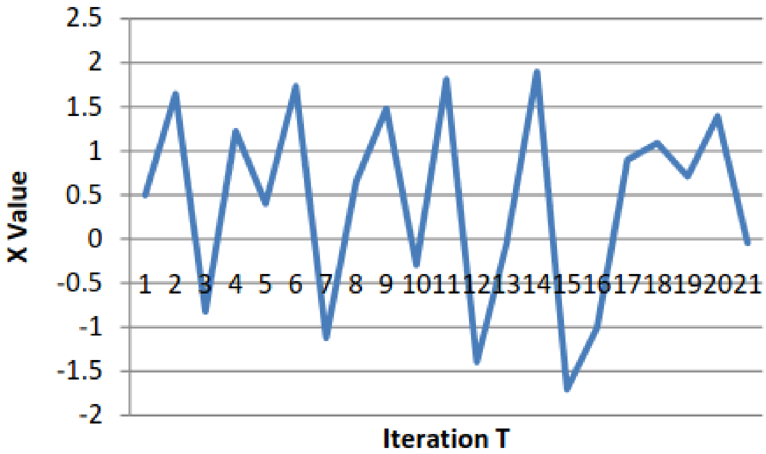

Figure1: Graph of One-Variable Chaos with initial conditions x =0.5

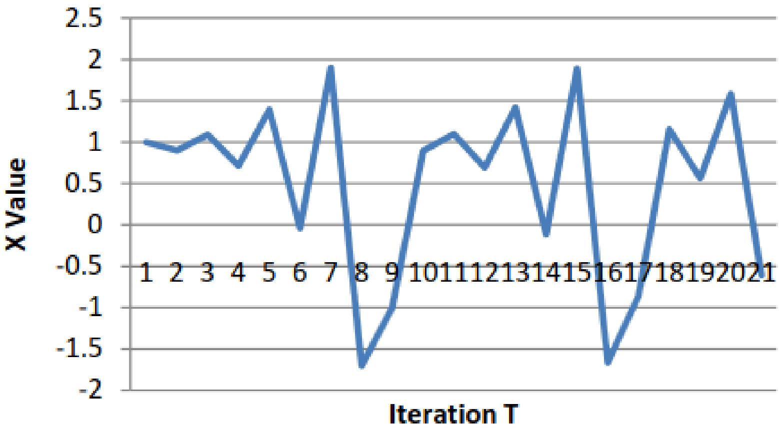

Figure2: Graph of One-Variable Chaos with initial conditions x =1.0

Obviously, the simulation results of the same equation show radically different behavior given a change in the initial conditions. This phenomenon explains the fact that while system short-term behavior can be predicted, it is practically impossible to predict its long-term behavior. Similarly, multi-variable chaos systems also show significantly different behavior for small perturbations in the initial conditions. Thus, for chaotic physical systems, any perturbation can change long-term behavior. Due to the chaotic behavior of dynamic systems, it is unwise tomake premature predictions about climate change, and it is also difficult to do any calculations with perfect accuracy since the climate change depend on so many factors. Thus, any inaccuracy in the initial condition of these variables will have consequences on the final outcome.

Modeling the Global Climate System

According to Mihailovic et al. (2014), proper supply of any complex system with energy is one important condition for the functioning of system. The dynamics of energy flow in a climate system follows the flow diagram of Mihailovicetal. (2014), shown in figure3.

The dynamics of flow of energy in any climate system is based on the energy balance equation (Stull, 1988). General difference form of energy balance equation for the ground surface as an environmental interface is;

$$C_g \frac{\Delta T}{\Delta t} = R_{net} - H - \lambda E - G \qquad (2)$$

where T_g is the ground surface temperature, $\Delta t$is the time step, $C_g$is the soil heat capacity, R_{net} is the net radiation, H is the sensible heat flux, $\lambda E$is the latent heat flux, and G is the heat flux into the ground.

$$R_{net} = C_R(T_g - T_a)(3)$$

where$C_R$is the coefficient for the net radiation term and $T_a$is the air temperature at some reference level (Bhumralkar, 1975). Again, the conduction of heat into the ground can be written in the form;

$$G = G_D(T_g - T_d)(4)$$

Where C_D is the coefficient of heat conduction and T_d is the temperature of the deeper soil layer.

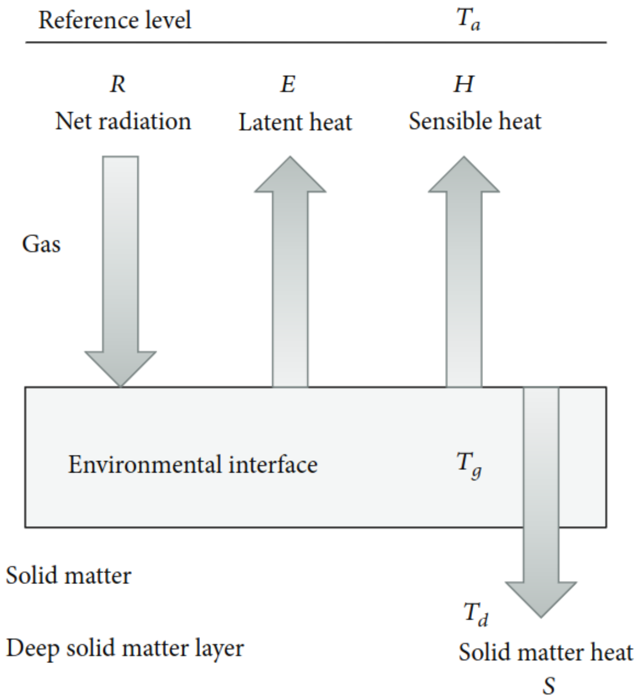

Figure 3: The dynamics of Energy flow in Climate System

Further, we can expand the exponential term in λE as;

$$\lambda E = C_L d\left[b(T_g - T_a) + \frac{b^2}{2}(T_g - T_a)^2\right] \quad (5)$$

Where C_L is the water vapor transfer coefficient b=0.06337$^0C^{-1}$, and d is a parameter. Finally, the sensible heat flux H is written as

$$H = C_H(T_g - T_a)(6)$$

Where C_H is the sensible heat transfer coefficient. In addition to the energy balance equation, an equation for temperature of the deeper soil layer is written as;

$$\frac{\Delta T}{\Delta t} = \frac{1}{\tau}(T_g - T_a) \quad (7)$$

Where τ=86400s. Substituting equations (3)-(6) into (2), and using the time forward in time and diving through by T_0 we obtain the coupled system

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$$\frac{T_g^{n+1}-T_a}{T_0} = \frac{T_g^n-T_a}{T_0} + \frac{\Delta t}{C_g} C_R \frac{T_g^n-T_a}{T_0} - \frac{\Delta t}{C_g} C_H \frac{T_g^n-T_a}{T_0} - \frac{\Delta t}{C_g} C_L bd \frac{T_g^n-T_a}{T_0} - \frac{\Delta t}{C_g} C_L d T_0 \frac{b^2}{2} \frac{\left(T_g^n-T_a\right)^2}{T_0} - \frac{\Delta t}{C_g} C_D \frac{T_g^n-T_a}{T_0} + \frac{\Delta t}{C_g} C_D \frac{T_d^n-T_a}{T_0} \quad (8)$$

$$\frac{T_d^{n+1}-T_a}{T_0} = \frac{T_d^n-T_a}{T_0} + \frac{\Delta t}{\tau} \frac{T_g^n-T_a}{T_0} - \frac{\Delta t}{\tau} \frac{T_d^n-T_a}{T_0} \quad (9)$$

The dimensionless environmental interface temperature $x = \frac{T_g-T_a}{T_0}$ and deeper soil layer temperature $y = \frac{T_d-T_a}{T_0}$ are introduced which simplifies (8) and (9) to the system;

$$x_{(n+1)} = Ax_n - Bx_n^2 + Cy^n, \quad (10)$$

$$y_{(n+1)} = Dx_n + (1-D)y_n, \quad (11)$$

where *A*, *B*, *C* and *D* are defined in Mihailovic et al., (2014) as:

$$A = 1 + \frac{\Delta t}{C_g}(C_R - C_H - C_L bd - C_D), B = C_L d T_0 \left(\frac{b^2 \Delta t}{2C_g}\right), C = \Delta t \frac{C_D}{C_g}, D = \frac{\Delta t}{\tau} \quad (12)$$

With parameter values chosen as $A \in [0, 4]$ and *B*, *C*, and *D* are ranged in the interval [0, 1] (Mihailovicetal., (2014), Mimicetal., 2013).

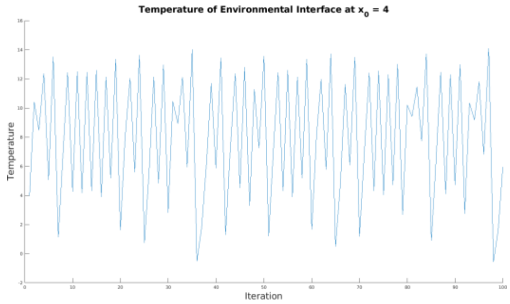
RESULTS AND DISCUSSIONS

In this section, the results of the model obtained are discussed. The dynamical system representing the global climate system was then implemented in MATLAB with parameter values *A*= 3.3, *B* = 0.25, *C* = 0.3 and *D* = 0.6. For different initial values of the environmental interface temperature *x*, an arbitrarily small change or perturbation of the initial values led to significantly different future behavior, thus making the system sensitive to initial conditions. The effect commonly known as the “butterfly effect”.

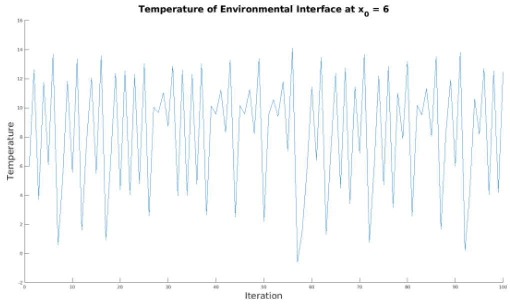
From figures 4 and 5, increasing the initial values of x0 and y0, resulted in different chaotic behavior. With the same parameter values A = 3.3, B = 0.25, C = 0.3 and D = 0.6, we observe a linear graph with no fluctuations, leading to static equilibrium of the dynamical system for initial values of x0 and y0 going beyond 11.9 as as shown figures 4-f and figure 6-f.

Although, we observe equilibrium system for initial values of x_0 and y_0 at 12 and beyond for A = 3.3, different dynamics of the climate system showing chaos with no static equilibrium was observed for different values of *A*, as shown in figure 6. This shows the effect of the parameter values *A* on both environmental interface and deeper soil temperature. Thus, from equation 12, it is evident that the soil heat capacity C_g, the water vapor transfer coefficient C_L, and other parameters in equation 12 have significant effect on the temperature of the environment and deeper soil which consequently affect climate change.

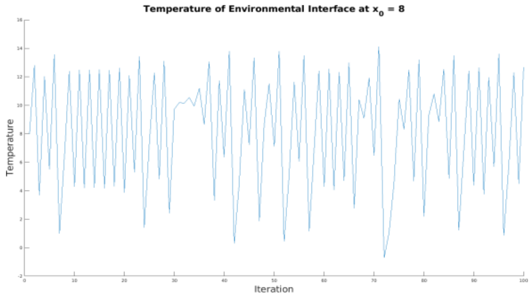
The environmental interface temperature and the deeper soil temperature were compared forsomechosenvaluesof*A*andinitialconditions.Theresultsofthesimulationareshowninfigure 7. It is observed that, at same initial conditions, the environmental interface temperatures at each iteration is higher than the temperature values of deeper soil.



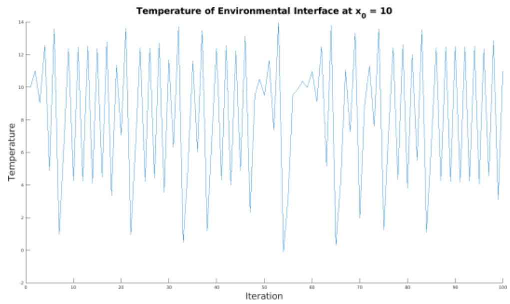
(a) Environmental Interface Temperature, $x0$ =4



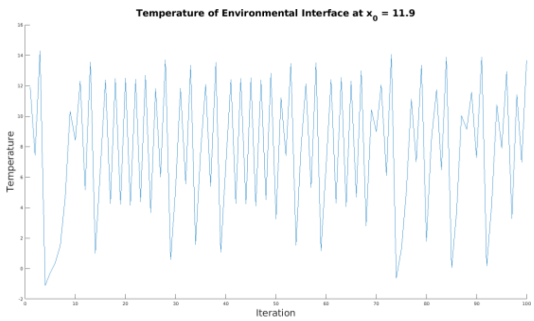
(b)Environmental Interface Temperature, $x0$=6



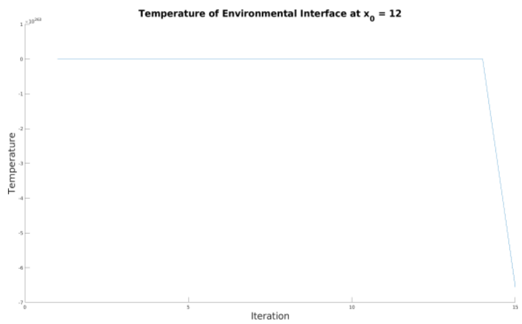
(c) Environmental Interface Temperature, $x0$ =8



(d)Environmental Interface Temperature, $x0$ =10



(e) Environmental Interface Temperature, $x0$ = 11.9



(f)Environmental Interface Temperature, $x0$ = 12

Figure4: Temperature of Deeper Soil Layer at different initial values of temperature x for parameter values A=3.3,B=0.25,C=0.3 and D=0.6

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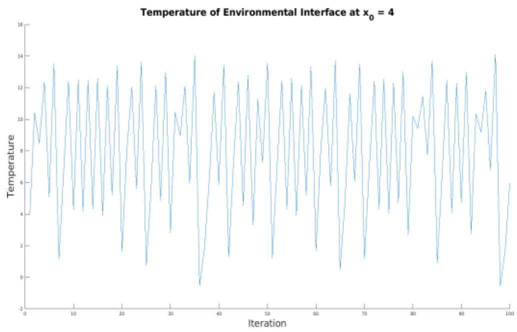
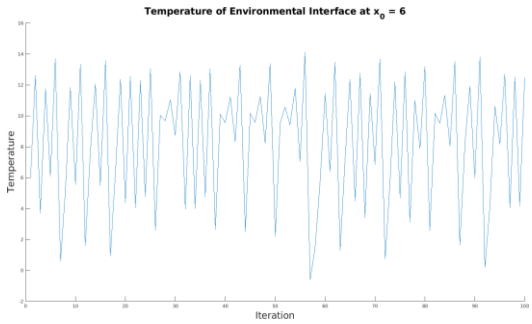
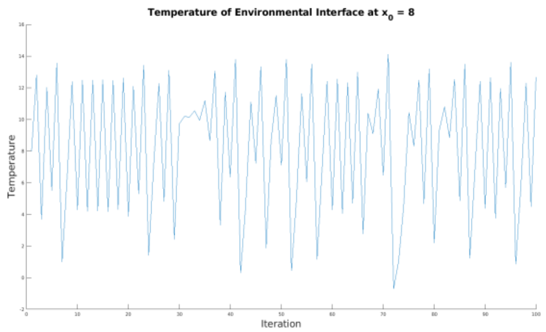


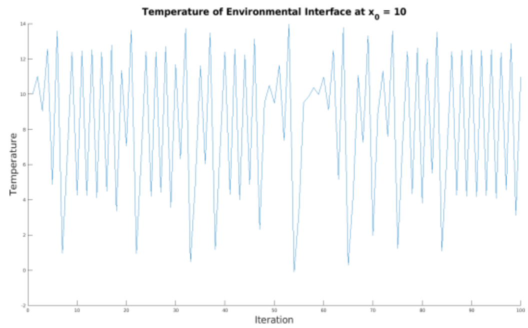
(a) Deeper Soil Layer Temperature, y0=4



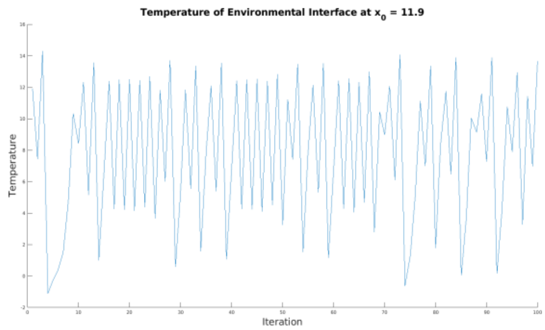
(b)Deeper Soil Layer Temperature, y0=6



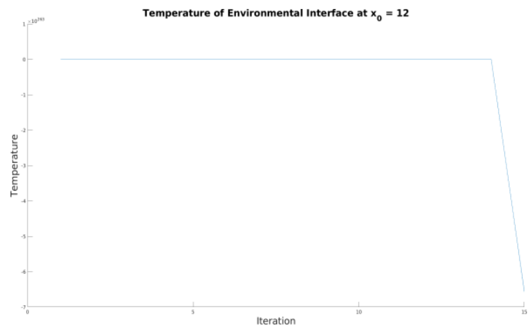
(c) Deeper Soil Layer Temperature, y0=8



(d)Deeper Soil Layer Temperature, y0= 10

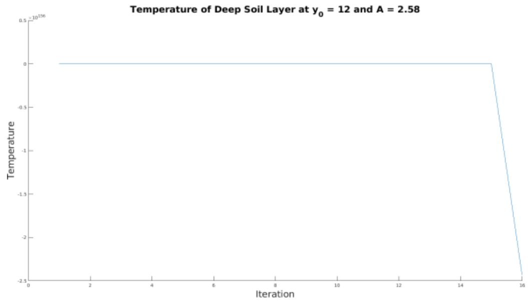


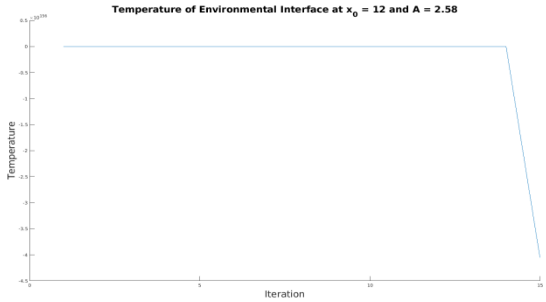
(e) DeeperSoilLayer Temperature, y0= 11.9



(f)DeeperSoilLayer Temperature, y0= 12

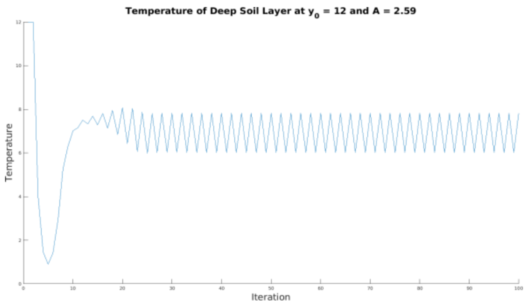
Figure5: Temperature of Environmental Interface at different initial values of temperature x for parameter values A =3.3, B=0.25,C=0.3and$D$=0.6.

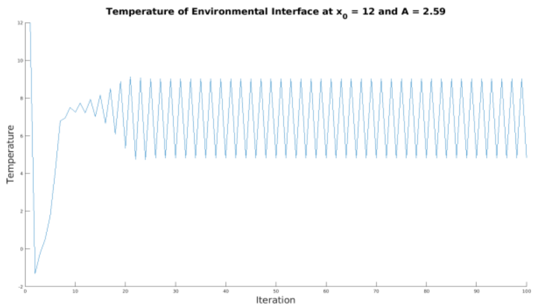




(a) Deeper SoilLayer Temperature, *A*=2.58

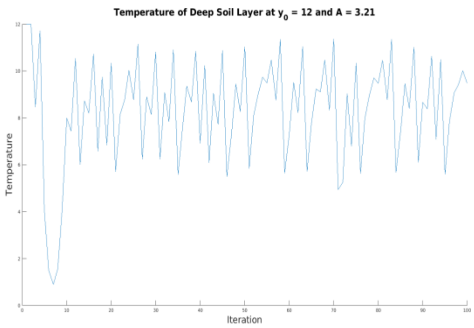
(b)Environmental Interface Temperature, *A*=2.58

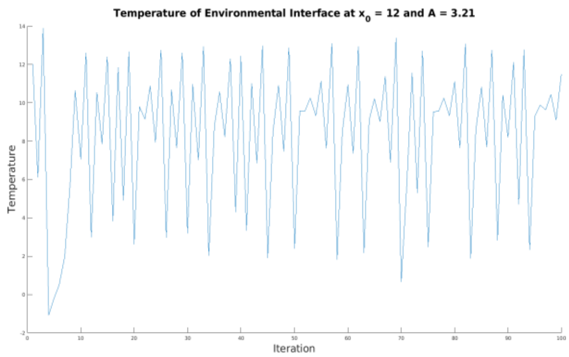




(c) Deeper Soil Layer Temperature, *A*=2.59

(d)Environmental Interface Temperature, *A*=2.59





(e) Deeper Soil Layer Temperature, *A*=3.21

(f)Environmental Interface Temperature, *A*=3.21

Figure6: Temperature fluctuations for both deeper soil and environment for *A*=3.21 beyond which no fluctuations observed

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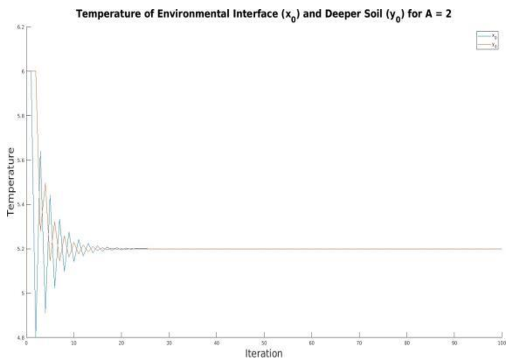
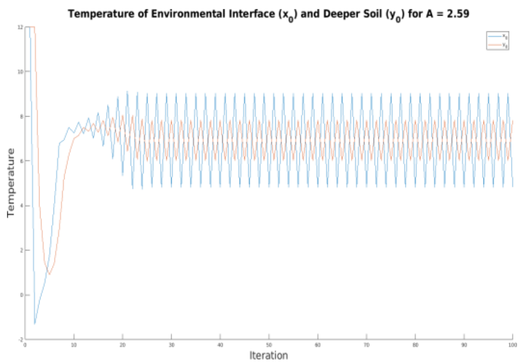
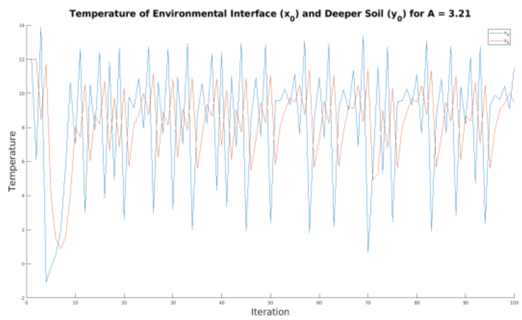


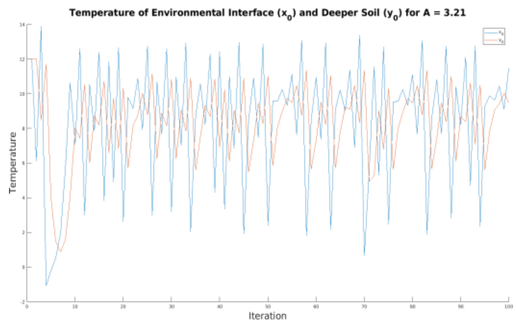
(a) Environmental and Deeper Soil Temperature



(b)Environmental and Deeper Soil Temperature



(c)Environmental and Deeper Soil Temperature

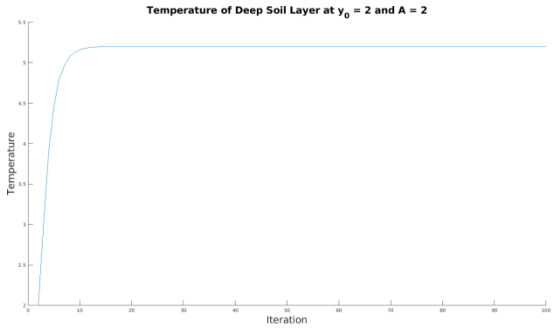


(d)Environmental and Deeper Soil Temperature

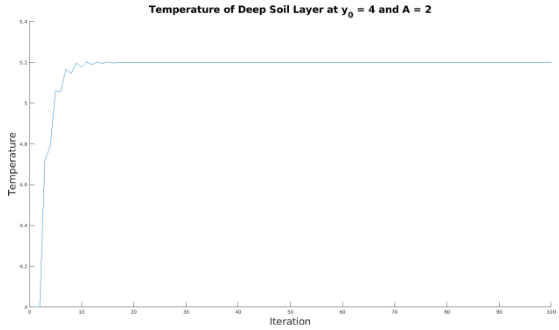
Figure 7: Comparing temperature fluctuations for both deeper soil and environmental interface at different initial conditions and parameter values A

At A=0,4, we always observe a linear graph with no fluctuations for all initial values x_0 and y_0 of environmental and deeper soil temperatures respectively. Again, for parameter values of A below 2.59, it is evident from figure 6, that a linear graph is observed for initial values of x_0 and y_0 more than or equal to12.

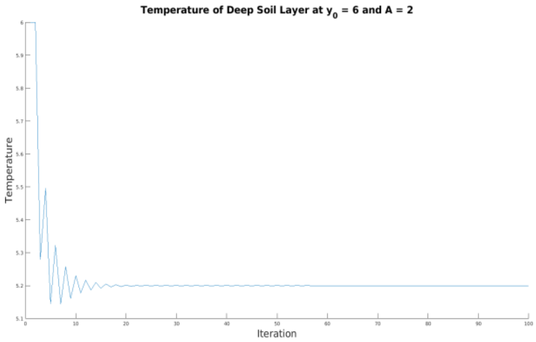
Further analysis of the values of A was carried out between 2 and 2.59 which give slow fluctuations leading to a static equilibrium system, at the first 18 iterations for initial values of x_0 and y_0 between 0 and 9.8 beyond which a linear graph is observed as shown in figure 8 and figure 9.



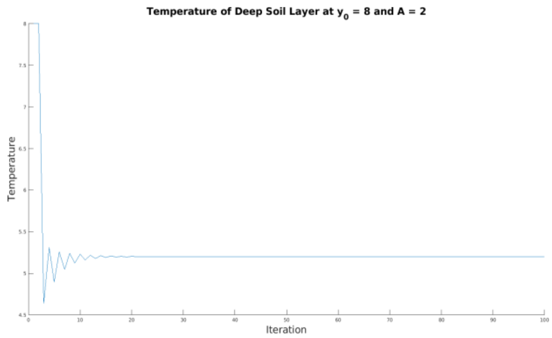
(a)Deeper Soil Layer Temperature, $x0$=2



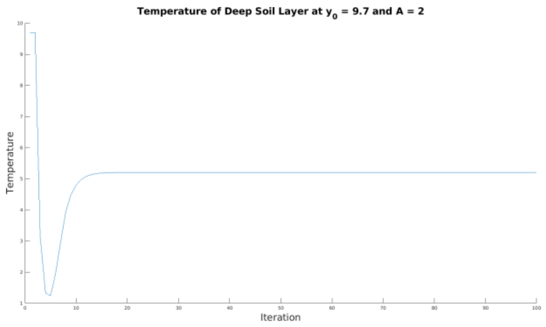
(b)Deeper Soil Layer Temperature, $x0$=4



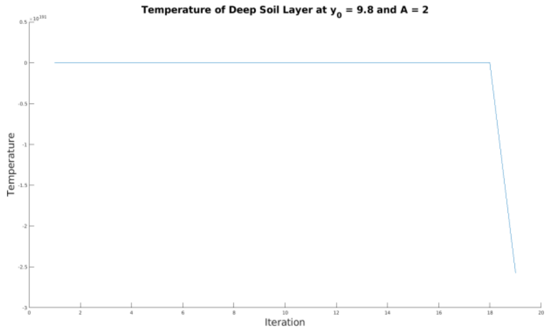
(c)Deeper Soil Layer Temperature, $x0$= 6



(d)Deeper Soil Layer Temperature, $x0$= 8



(e)Deeper Soil Layer Temperature, $x0$= 9.7



(f)Deeper Soil Layer Temperature, $x0$= 9.8

Figure 8: Temperature fluctuations for deeper soil for A=2with varying initial conditions

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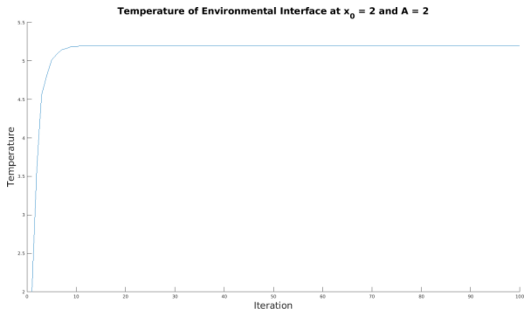
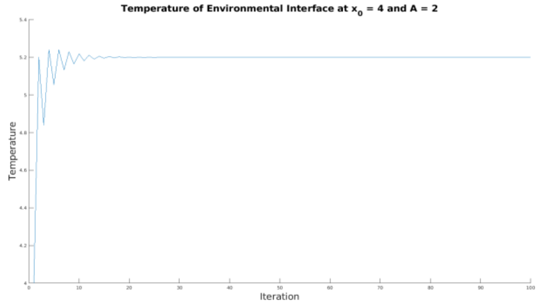
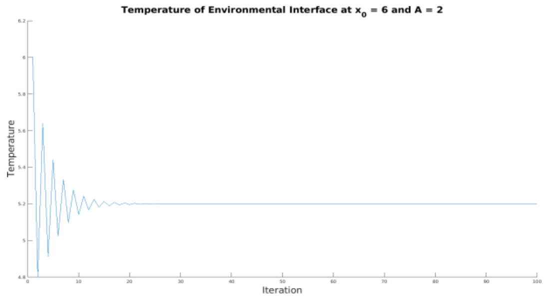


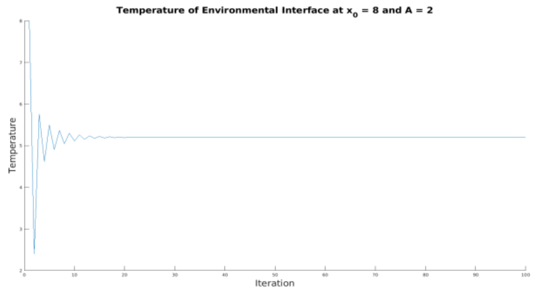
(a) Environmental Interface Temperature, $x0$ =2



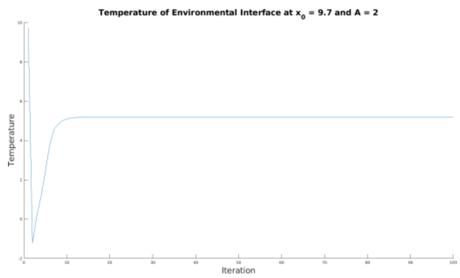
(b) Environmental Interface Temperature, $x0$ = 4



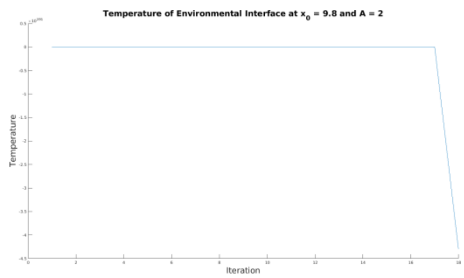
(c)Environmental Interface Temperature, $x0$ = 6



(d) Environmental Interface Temperature, $x0$ = 8



(e)Environmental Interface Temperature, $x0$ = 9.7



(f) Environmental Interface Temperature, $x0$ = 9.8

Figure 9: Temperature fluctuations for both deeper soil and environment for A=3.21 beyond which no fluctuations observed

CONCLUSION

Climate change is a prime example of a chaotic system. Unfortunately, the concept of chaos is poorly understood within most business, social science, and military literature. Climate change according to literature is a complex phenomenon which depends on so many factors. To understand the impact of climate change, the theory of chaos is proposed which is investigated in this study. In this study, a model is developed from the dynamics of energy flow in a climate system, which incorporates environmental interface temperature and deeper soil temperature. Many factors affecting the climate system such as soil heat capacity, sensible heat capacity, la-tent heat capacity, air temperature and net radiation, and others, were captured in the model. The analysis of the model obtained revealed that, the environmental interface temperature and the deeper soil temperature shows different chaotic behavior for different initial conditions. Also, for different parameter values of A and other parameters B, C, and D, which incorporates these environmental factors, had significant effect on environmental and deeper soil temperatures. In future studies, it is recommended that, other factors that affect the climate be considered.

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