# Climate Change Dynamics

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## 1 Introduction

The issue of climate change is considered to be one of the most critical global concerns of the present era. The effects of climate change, including the elevation of sea levels, the amplification of occurrence and severity of extreme weather events, and the decline of biodiversity, are being experienced on a global scale. In order to tackle and adapt to the effects of climate change, it is crucial to possess a thorough understanding of the complex mechanics that govern the Earth's climate system.

System Dynamics Modelling is a powerful tool that can help us better understand the feedback loops and interactions between various climate system components, including the atmosphere, oceans, land surface, and biosphere. By creating a simulation model of the climate system, we can test different scenarios and interventions to see how they affect the Earth's short- and long-term climate.

The purpose of this project is to create a System Dynamics Model that mimics the Earth's climate system and investigates how various factors, such as greenhouse gas emissions, changes in land use, and human intervention, impact climate change. By running simulations of different scenarios and interventions, we aim to offer useful insights into the most effective strategies for mitigating climate change. Our ultimate objective is to contribute to the development of a sustainable future for everyone.

## 2 Problem Statement

Climate change [2] is caused by the accumulation of greenhouse gases in the atmosphere, which traps heat and increases the Earth's temperature over time. However, this is just one aspect of a much larger and more complex system, including land use, deforestation, energy consumption, and more.One of the primary difficulties in addressing climate change is grasping the interdependence of different factors and how alterations in one area of the system can trigger consequences across the entire system. Understanding climate change's complex and interrelated factors is crucial in developing effective strategies and interventions to mitigate its effects. With a comprehensive understanding of the underlying dynamics and feedback loops that drive the system, efforts to address climate change may stay within their intended impact. Therefore, it is vital to prioritize research and modelling efforts that can help us gain deeper insights into the complex systems that contribute to climate change.

## 3 Background

Climate change has emerged as one of humanity's most significant challenges in the 21st century. The Earth's climate is complex, with numerous feedback loops and interactions between the atmosphere, oceans, land surface, and biosphere. Human actions, such as the burning of fossil fuels and deforestation, are the primary sources of the surge in greenhouse gas emissions that have resulted in a global temperature increase.

As per the Intergovernmental Panel on Climate Change (IPCC), the Earth's climate will continue to warm, and disastrous consequences such as increased frequency and severity of heatwaves, droughts, floods, and storms, will be inevitable unless there are prompt and significant reductions in greenhouse gas emissions. These impacts, in turn, will have severe consequences for ecosystems, human health, and the economy.

System Dynamics Modelling has emerged as a powerful tool to help us better understand the complexity of the Earth's climate system and predict the impacts of different interventions to mitigate and adapt to climate change. It is a mathematical and computational approach that can capture feedback loops and non-linear relationships between different climate system components.

# 4 Literature Survey

Several studies have utilized System Dynamics Modelling to investigate the impacts of climate change and potential interventions to mitigate and adapt to its impacts.

In a study by Sterman et al. (2018) that utilized System Dynamics Modelling, the researchers examined several carbon pricing policies to determine their potential for reducing greenhouse gas emissions. Their research indicated that a carbon tax combined with revenue-neutral rebates was the most effective policy in decreasing emissions while also maintaining economic growth.

In a study conducted by O'Brien and colleagues (2020) using System Dynamics Modelling, they investigated the impact of land use changes on climate change. Their results showed that taking measures such as decreasing deforestation rates and increasing afforestation and reforestation efforts could considerably decrease greenhouse gas emissions while improving the carbon sequestration process.

Similarly, Zhang et al. (2020) utilized System Dynamics Modelling to explore the potential of renewable energy sources in mitigating greenhouse gas emissions. The study revealed that shifting towards renewable energy sources and implementing energy-efficient measures could significantly reduce emissions while also providing economic benefits.

Collectively, these studies emphasize the significance of System Dynamics Modelling in influencing policy formulation and decision-making in the realm of climate change. By simulating diverse scenarios and interventions, System Dynamics Modelling has the potential to provide valuable insights into the most effective methods to tackle climate change while minimizing any unfavorable economic and social impacts.

## 5 CLD

This is CLD for Climate change.

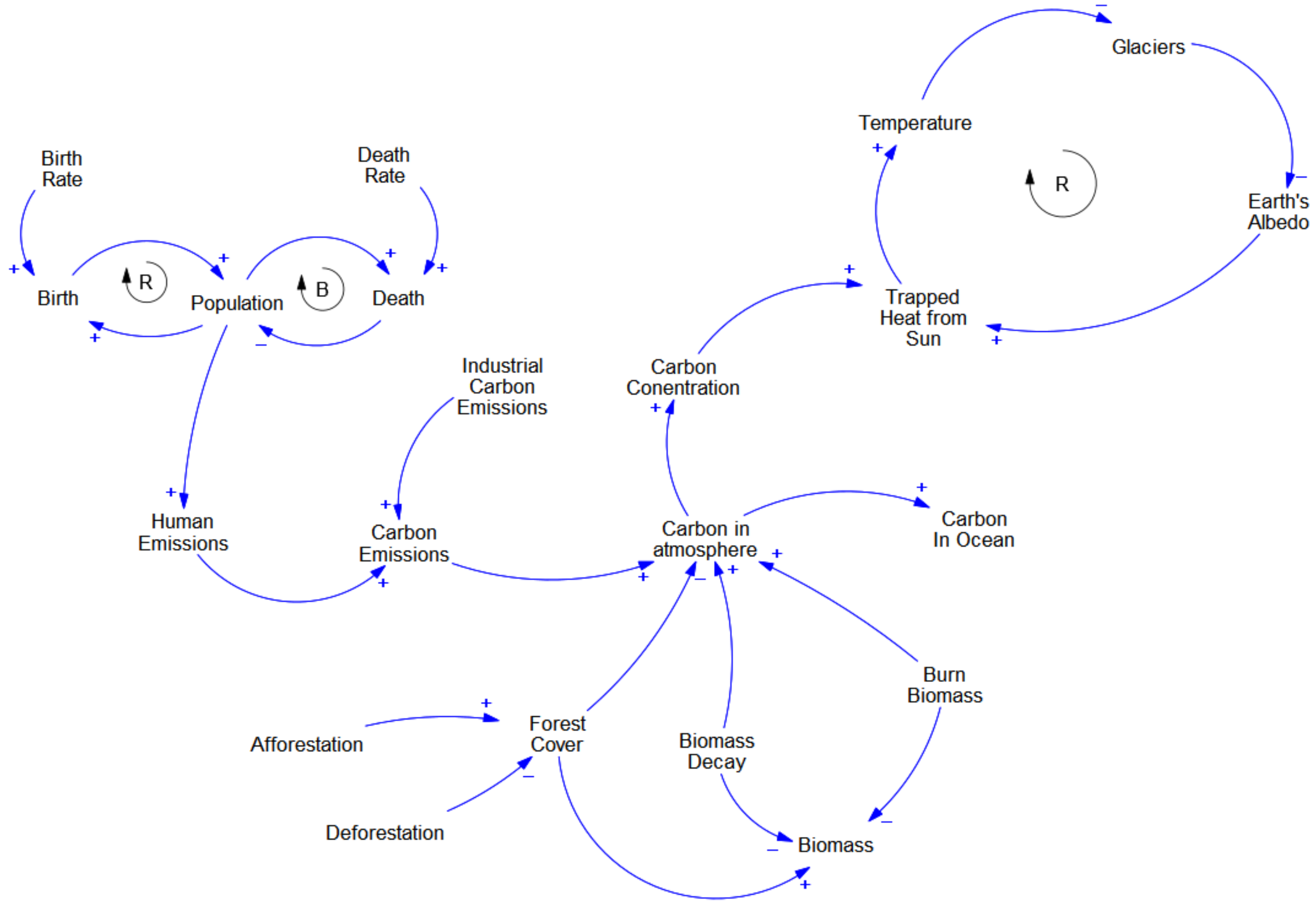


Figure 1: Causal Loop Diagram (CLD) for Climate Change

# 6 SFD

This is the SFD for Climate Change

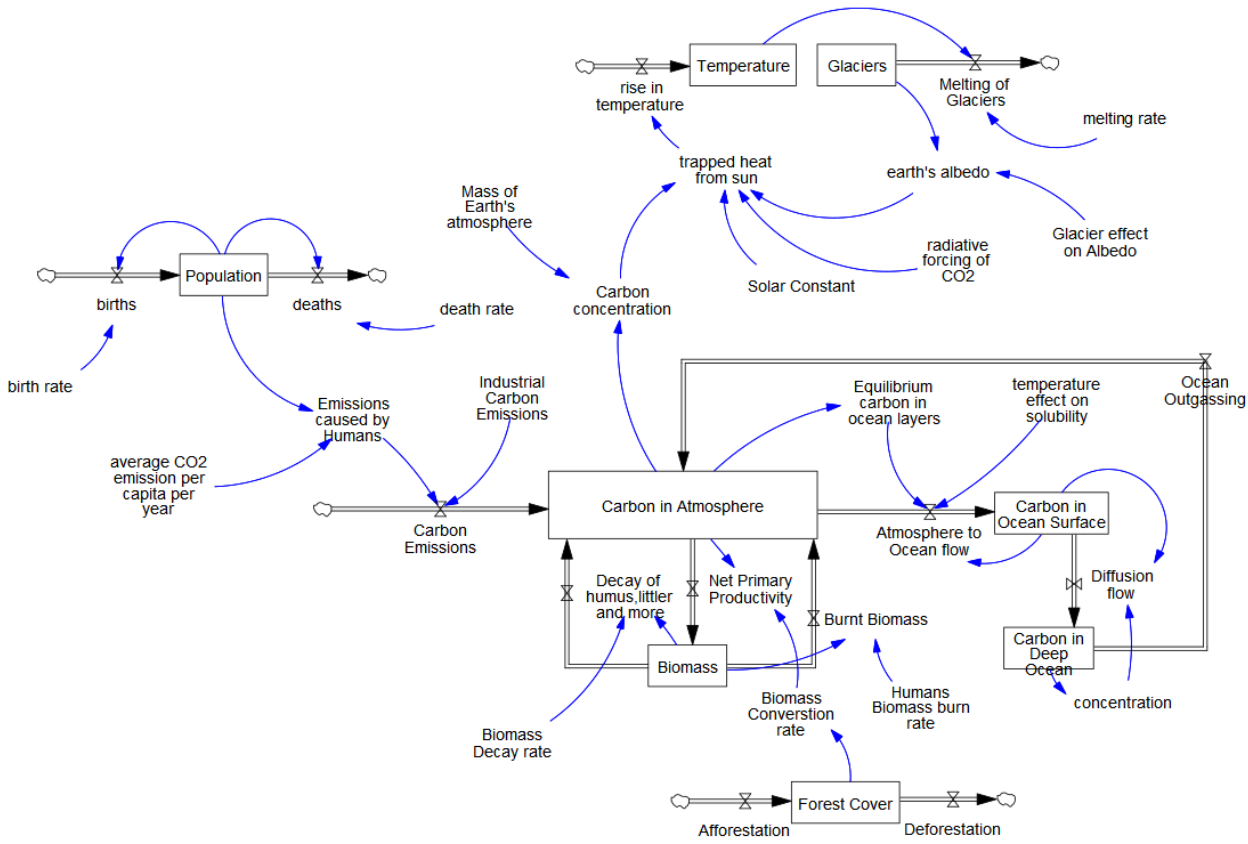


Figure 2: Stock Flow Diagram (SFD) for Climate Change

## 6.1 Stocks

1. Carbon in Atmosphere: The amount of carbon dioxide ($CO_2$) present in the Earth's atmosphere, which is a major contributor to climate change.
2. Biomass: The amount of living biological material on Earth, including plants and animals.
3. Carbon in Ocean Surface: The amount of $CO_2$ dissolved in the upper layer of the Earth's oceans.
4. Carbon in Deep Ocean: The amount of $CO_2$ stored in the deep layers of the Earth's oceans.
5. Forest Cover: The amount of forested land on Earth, which plays an important role in absorbing and storing carbon.
6. Population: The number of humans living on Earth, which contributes to carbon emissions through activities such as transportation and energy use.
7. Temperature: The average global temperature, which is affected by climate change.
8. Glaciers: The amount of ice present in glaciers and ice sheets, which are melting due to climate change.

## 6.2 Flows

1. Births: The number of human births per year, which contributes to population growth and carbon emissions.
2. Deaths: The number of human deaths per year, which affects population growth.
3. Decay of humus, litter and more: The breakdown of organic matter, which releases carbon into the atmosphere.
4. Net Primary Productivity: The amount of carbon absorbed by plants through photosynthesis.
5. Burnt Biomass: The burning of trees and other plant material, which releases carbon into the atmosphere.
6. Atmosphere to Ocean flow: The exchange of carbon dioxide between the atmosphere and the ocean.
7. Diffusion flow: The movement of gases such as CO2 and oxygen between the atmosphere and the surface of the Earth.
8. Afforestation: The planting of new forests, which can absorb and store carbon.
9. Deforestation: The clearing of forests, which releases carbon into the atmosphere.
10. Ocean Outgassing: The release of carbon from the ocean into the atmosphere.
11. Carbon Emissions: The release of carbon into the atmosphere through human activities such as burning fossil fuels and deforestation.
12. Rise in temperature: The increase in global temperature due to climate change.
13. Melting of Glaciers: The melting of glaciers and ice sheets due to climate change.

## 6.3 Variables

1. Birth Rate: The rate at which human births occur.
2. Death Rate: The rate at which human deaths occur.
3. CO2 emission per capita per year: The amount of carbon emissions per person per year.
4. Emissions caused by Humans: The total amount of carbon emissions caused by human activities.
5. Industrial Carbon Emissions: The amount of carbon emissions produced by industrial processes.
6. Biomass Decay Rate: The rate at which organic matter decays and releases carbon into the atmosphere.
7. Biomass Conversion Rate: The rate at which plants absorb carbon through photosynthesis.
8. Human Biomass Burn Rate: The rate at which humans burn biomass for energy, releasing carbon into the atmosphere.
9. Equilibrium carbon in ocean layers: The amount of carbon that the ocean can absorb and store in different layers.
10. Temperature effect on solubility: The effect of temperature on the solubility of gases such as carbon dioxide in the ocean.

11. Mass of Earth's Atmosphere: The total mass of the Earth's atmosphere, which affects the concentration of gases such as carbon dioxide.
12. Carbon Concentration: The concentration of carbon dioxide in the atmosphere.
13. Solar Constant: The amount of solar radiation that reaches the Earth's surface.
14. Radiative forcing of of CO2: The effect of carbon dioxide on the Earth's energy balance.
15. Trapped heat from sun: Amount of Heat Trapped by Sun per unit area.
16. Earth's Albedo: The reflectivity of the Earth's surface, which affects how much solar radiation is absorbed and how much is reflected.
17. Melting Rate: The rate at which glaciers and ice sheets are melting due to climate change.
18. Concentration: The concentration of greenhouse gases in the atmosphere, which affects the Earth's energy balance.
19. Glacier effect on Albedo: The effect of melting glaciers on the Earth's reflectivity, which can further contribute to climate change.

## 6.4 Equations for Stocks

1. Carbon in Atmosphere += Burnt Biomass + Carbon Emissions+Decay of humus,littler and more + Ocean Outgassing - Atmosphere to Ocean flow - Net Primary Productivity
   INITIAL VALUE = 3000
   UNITS = Gt (Giga Tons)
2. Biomass += Net Primary Productivity - Burnt Biomass - Decay of humus,littler and more
   INITIAL VALUE = 2000
   UNITS = Gt (Giga Tons)
3. Carbon in Ocean Surface += Atmosphere to Ocean flow - Diffusion flow
   INITAL VALUE = 3000
   UNITS = Gt (Giga Tones)
4. Carbon in Deep Ocean += Diffusion flow - Ocean Outgassing
   INITIAL VALUE = 2000
   UNITS = Gt (Giga Tones)
5. Forest Cover += Afforestation - Deforestation
   INITAL VALUE = 4060 UNITS = MHectare (Million Hectare)
6. Population += births-deaths
   INITAL VALUE = 7 Billion
   UNITS = People
7. Temperature += rise in temperature
   INITAL VALUE = 15
   UNITS = C (Celcius)
8. Glaciers -= (Temperature - 15) * melting rate
   INITAL VALUE = 706000
   UNITS = sq meter

## 6.5 Equations for Flows

1. Births = Birth Rate * Population
   UNITS = People/Year

2. Deaths = Death Rate * Population
   UNITS = People/Year

3. Decay of humus, litter and more = Biomass * Biomass Decay rate
   UNITS = Gt/Year

4. Net Primary Productivity
   UNITS = Gt/Year

5. Burnt Biomass = Humans Biomass burn rate * Biomass
   UNITS = Gt/Year

6. Atmosphere to Ocean Flow = (Equilibrium carbon in ocean layers - Carbon in Ocean Surface) * temperature effect on solubility
   UNITS = Gt/Year

7. Diffusion Flow = Carbon in Ocean Surface/concentration
   UNITS = Gt/Year

8. Afforestation = 5 (CONSTANT)
   UNITS = MHectare/Year

9. Deforestation = 20 (CONSTANT)
   UNITS = MHectare/Year

10. Ocean Outgassing = 40 (CONSTANT)
    UNITS = Gt/Year

11. Carbon Emissions = Emissions caused by Humans + Industrial Carbon Emissions
    UNITS = Gt/Year

12. Rise in temperature = trapped heat from sun * 0.0004
    UNITS = C/Year

13. Melting of Glaciers = (Temperature - 15) * melting rate
    UNITS = sq meter/Year

## 6.6 Equations for Variables

1. Birth Rate = 18.5/1000
   UNITS = 1/Year

2. Death Rate = 7.7/1000
   UNITS = 1/Year

3. CO2 emission per capita per year = 4.9
   UNITS = Ton/Year

4. Emissions caused by Humans = Population * average CO2 emission per capita per year/1e+09
   UNITS = Gt/Year

5. Industrial Carbon Emissions = 100
   UNITS = Gt/Year

6. Biomass Decay Rate = 0.05
   UNITS = 1/Year

7. Biomass Conversion Rate = 0.001 * Forest Cover / 100
UNITS = 1/Year

8. Human Biomass Burn Rate = 0.2
UNITS = 1/Year

9. Equilibrium carbon in ocean layers = Carbon in Atmosphere*0.4
UNITS = 1/Year

10. Temperature effect on solubility = 0.1
UNITS = 1/Year

11. Mass of Earth's Atmosphere = 5.148 * 1e+12
UNITS = kg

12. Carbon Concentration = Carbon in Atmosphere* 1e+12/(Mass of Earth's atmosphere)
UNITS = ppm

13. Solar Constant = 1370
UNITS = W/area

14. Trapped heat from sun = (Solar Constant*(1- earth's albedo)) + radiative forcing of CO2 * LOG(Carbon concentration/582, 2)
UNITS = W/area

15. radiative forcing of CO2 = 100
UNITS = W/area

16. Earth's Albedo = Glaciers * Glacier effect on Albedo
UNITS = 1

17. Melting Rate = 10000
UNITS = sq meter/(Year*C)

18. Concentration = Carbon in Deep Ocean/100
UNITS = Year

19. Glacier effect on Albedo
UNITS = 1/sq meter

# 7 Findings and Analysis

Our main focus in the SFD was on the stocks - Carbon in Atmoshphere and Temperature (here it is the average global temperature of the Earth) [1]. Carbon in Atmoshphere stock accumulates carbon in giga tonnes which are majorly contributed from biomass and carbon emissions. The carbon is circulated in the atmosphere, ocean and land (biomass). The biomass could be living biomass such as forests, trees and roots and dead biomass could be humus and charcoal.

Two primary mechanisms through which the ocean absorbs carbon from the atmosphere are at the ocean's surface and in the deep ocean.

The primary form of carbon absorbed at the ocean's surface is carbon dioxide (CO2) gas, which dissolves into the surface waters of the ocean. The process is driven by the difference in CO2 concentrations between the atmosphere and the surface waters of the ocean. CO2 reacts with water molecules to form carbonic acid, which can affect the marine life. The deep ocean stores carbon primarily as dissolved organic matter and inorganic carbon species, particularly bicarbonate and carbonate ions. While the concentration of carbon in the deep ocean is greater than in the surface ocean, the total amount of carbon stored in the deep ocean is significantly larger. As a result, the deep ocean serves as a long-term reservoir for carbon, with estimates indicating that it could hold as much as 50 times more carbon than the atmosphere.

The glaciers stock does not have any inflow because we assumed that glacier formation is very difficult and the stock will not accumulate any further values for glaciers. This assumption is made because of the constant rising temperature. We can also observe a feedback loop between stocks temperature and glaciers. It is a positive feedback loop. The rise in temperature inflow increases the temperature which results in melting of glaciers. So, our aim would be to keep the temperature at constant levels so that the glaciers don't melt rapidly in the upcoming time. We can see the glaciers are strongly related to Earths's albedo.

The albedo glacier temperature climate change feedback loop is a complex process that can speed up global warming. Its mechanism is as follows:

Albedo: Albedo refers to the amount of sunlight reflected by a surface. Surfaces that are bright and reflective, such as ice and snow, have a high albedo, which means they reflect more sunlight than they absorb. Conversely, dark surfaces like forests and oceans have a low albedo, meaning they absorb more sunlight than they reflect.

Glacier melting: With the rise in global temperatures, glaciers and ice caps melt at an accelerating rate. This leads to the exposure of more dark surfaces such as soil and rocks, which have a low albedo.

Reduced albedo: As more dark surfaces become exposed, the overall albedo of the Earth decreases. This causes the planet to absorb more sunlight, resulting in further warming.

Temperature increase: The increased absorption of sunlight leads to a rise in global temperatures, causing more glacier melting. The cycle perpetuates itself.

This feedback loop can have severe and potentially disastrous consequences on the planet's climate. As temperatures continue to climb, glaciers and ice caps melt more rapidly, which in turn reduces the Earth's albedo, leading to further warming. This can create a self-reinforcing cycle of climate change that is challenging to reverse.

We simulated the model for 10 years and observed that the temperature rises by 1.5 degree Celsius each year, where this could be slowed down or maintained in a specific range by increasing forest cover stock by increasing afforestation and decreasing deforestation. Also, we have to bring down the emissions caused by humans.

## References

[1] Mohammad Khaled Akhtar. *A system dynamics based integrated assessment modelling of global-regional climate change: a model for analyzing the behaviour of the social-energy-economy-climate system.* The University of Western Ontario (Canada), 2011.

[2] JW Li, YC Cao, YQ Zhu, C Xu, LX Wang, et al. System dynamic analysis of greenhouse effect based on carbon cycle and prediction of carbon emissions. *Applied Ecology and Environmental Research*, 17(2):5067–5080, 2019.