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THERMODYNAMIC MODELING AND ANALYSIS OF CLIMATE CHANGE AND EARTH SYSTEMS

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Abstract

Background: Climate change is fundamentally a thermodynamic phenomenon, driven by imbalances in the Earth's energy budget and amplified by feedback processes within the atmosphere, hydrosphere, cryosphere, and biosphere. Understanding climate dynamics from a thermodynamic perspective enables the identification of irreversible changes, entropy production trends, and limits to system resilience.

Objective: This study develops and applies a thermodynamic modeling framework to analyze climate change and Earth system dynamics, focusing on the interplay between radiative energy transfer, atmospheric composition changes, and feedback-driven entropy production. The aim is to provide a physically consistent basis for projecting long-term climate trajectories under various greenhouse gas emission scenarios.

Methods: Using the first and second laws of thermodynamics as foundational principles, an enhanced Earth energy balance model (EBM) was formulated to account for incoming solar radiation, albedo variability, greenhouse gas radiative forcing, and ocean heat uptake. Empirical datasets from satellite radiative flux measurements, atmospheric CO_2 concentration records, and global temperature anomalies were incorporated for model calibration. Numerical simulations were conducted across Representative Concentration Pathway (RCP) and Shared Socioeconomic Pathway (SSP) scenarios to evaluate the thermodynamic evolution of the climate system.

Results: Model simulations indicate a persistent positive radiative imbalance of 0.8–1.2 W/m² over recent decades, corresponding to continuous ocean heat uptake and rising entropy production in the climate system. Under high-emission scenarios, global mean surface temperature anomalies exceed 4 °C by 2100, with accelerated cryosphere melting and reduced planetary albedo. Entropy analysis reveals that anthropogenic forcing has shifted the climate system toward higher irreversibility, reducing its capacity for natural recovery without significant intervention.

Conclusion: Thermodynamic analysis provides a robust, physically grounded framework for understanding and predicting climate change. By linking energy balance disruptions with irreversible system changes, this approach complements traditional climate models and offers valuable insights for mitigation and adaptation strategies. Integrating thermodynamic constraints into Earth system modeling enhances the scientific basis for policy-making in the face of accelerating climate risks.

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INTRODUCTION

The Earth system is an extremely complex network of physical, chemical and biological activity that occurs at a wide variety of space and time scales. Climate change or rather manmade greenhouse gases contribution in causing climate change has emerged as one of the most significant scientific and even social issues of the XXI century (Masson-Delmotte et al., 2021). We should have a powerful theoretical basis to comprehend, predict and know how the climate system functions. A crude measure of energy exchanges, feedback loops, and irreversible processes that dominate (climate dynamics) can be obtained by thermodynamics (Kleidon, et al., 2020). Thermodynamic modelling can allow researchers to relate radiative forcing, atmospheric circulation, ocean heat transport and biosphere-atmosphere interaction within a single physical context.

The thermodynamic concept of climate change derives a perspective of Earth as a non-equilibrium thermodynamic system which is continuously exchanging energy with its environment. This occurs mainly when the Earth traps solar radiation and releases them as longwave infrared radiation (Lucarini, et al., 2020). The balance between energy input and out opposes the average temperature of the planet. Ocean and atmospheric circulation are brought together due to changes in this balance, over time and distance. The energy balance will be altered due to climate change, increase the concentrations of greenhouse gases, aerosol forcing, and land use altering the rate of entropy formation and effectiveness of the energy conversion processes within the climate system (Goosse, et al., 2019).

According to Kleidon et al. (2020), the climatic system of the Earth may be considered as a thermal machine, which transforms part of the solar power received on its surface into the amount of force, dominantly through the motion of air and water. The difference in temperature between the hot tropics and cold poles influences the effectiveness of this climatic heat engine. climatic change alters this gradient by altering the rates at which different places heat up. As an example, the meridional temperature gradient is reduced by Arctic amplification, the warming of high latitudes at a rate greater than that of lower latitudes. This, consequently, affects the effectiveness of massive circulation patterns (Pithan et al., 2018).

The Earth system is an incredibly complex intertwining of physical, chemical and biological processes that occur on a wide variety of space and time scales. Climate change that is primarily human-generated through greenhouse gas emissions has turned out to be one of the most relevant scientific and social problems in the 21 st century (Masson-Delmotte et al., 2021). A powerful theoretical construct is required to comprehend how the climate system functions and to be able to foresee it. With thermodynamics, we have a simple method of quantifying exchanges of energy, of feedback loops, and of irreversible processes governing climate dynamics (Kleidon, et al., 2020). Thermodynamic modelling enables a researcher to relate radiative forcing, atmospheric circulation, heat transport in the ocean, and biosphere-atmosphere interactions within the same physical environment.

The thermodynamic perspective of climate change is underpinned with the notion that the earth is a non equilibrium thermodynamic system maintained in continual energy flux with that of its surroundings. This occurs primarily when the earth is subjected to absorption of sunlight and releases longwave infrared light (Lucarini, et al., 2020). Energy flow into the planet and that leading out determines the average temperature. Any time and spatial variations in this balance bring about the ocean and atmospheric circulation. The changing energy balance brought about by climate change increases the concentration of greenhouse gases, aerosol forcing, and land use, which alters the rate of entropy generation and energy conversion progress in the climate system (Goosse, et al., 2019).

According to Kleidon et al. (2020), the climate system of the earth may be considered as a heat engine and uses the solar energy that it collects to convert part of this energy into mechanical work, primarily in the form of air and water motion. The disparity between the hot moderate and the cold polar climates influences the effectiveness of this climatic heat engine. climatic change alters this gradient by altering the warming rates of diverse regions. As an example, arctic amplification, that is, high latitudes warm at a faster rate, brings about a reduction of the meridional temperature difference. In its turn, this affects the effectiveness of the large-scale circulation patterns (Pithan et al., 2018). Thermodynamic modelling also comes in handy in the determination of what leads to extreme weather such as heatwaves, hurricanes and droughts. During such events, there is normally a large change in energy and moisture movements. Scientists analyse thermodynamic predictors such as thermodynamic moist static energy, potential strength and convective available potential energy to determine the probability and intensity of their occurrence in a warming climate (Knutson, et al., 2020). The proxy data can also be used to advance the reconstructions of paleoclimate since thermodynamic interpretations allow us to speculate about past temperature variations, ice volume changes, and levels of CO 2 in the atmosphere (Tierney, et al., 2020).

The inclusion of thermodynamic principles with the Earth system models (www.mri.org) also increases their ability in policy-relevant climate predictions. ESMs with thermodynamic constraints perform more acutely in simulating shifts in regional climatical trends, hydrological cycle, and long-term climatic stabilisation ordinances in various climate change reduction scenarios (Tokarska, et al., 2020). This plays a great role in devising means of adapting and reducing the impact of climate change on ecosystems, economies, and the human society.

To sum it up, the use of thermodynamic modelling and analysis as a tool to view climate change and the Earth system is quite convenient. Since 2018 observational data, improved computer models, and new theories have enabled us to know more about energy flows and feedback loops leading to climate change and interannual variability over time horizons. Thinking about the climate system as a complex, open thermodynamic system, researchers can measure causes of climate change more effectively, test the validity of models, and identify options to bring about a stable and sustainable climatic future.

METHODOLOGY

The paper applies a mixed-methods research methodology that has integrated thermodynamic theory, quantitative numerical modelling, and actual climate information in the study of the impact of human activity on the earth in terms of energy and entropy over time. The technique is founded on the first and the second law of thermodynamics. They provide a physically homogeneous method to discuss the way in which energy varies and circulates within the climate system. The modelling begins by formulation of a better formula of the energy balance of the Earth.

$$C\frac{dT}{dt} = S(1-\alpha) - \epsilon\sigma T^4 + F_{\mathrm{GHG}}$$

with C being the effective heat capacity of the earth, T being the average global surface temperature, S the solar constant, a the planetary albedo, e the effective emissivity, s the StefanBoltzmann constant and FGHGHF the radiative forcing due to anthropogenic greenhouse gases. This equation considers shortwave radiation coming in to the Earth, the reflection of light by clouds and surface features, radiative cooling of longwave radiation and greenhouse gases which trap additional infrared radiation.

Entropy production study looks at the irreversible processes in the climate system by using the second rule of thermodynamics. This can be illustrated by the fact that:

$$\sigma_{\text{prod}} = \sum_i \frac{J_i X_i}{T}$$

where JiJ denotes generalized fluxes such as heat transport and atmospheric circulation, XiX_ represents the associated thermodynamic forces, and T is the local temperature field. This formulation enables quantification of how radiative imbalances, ocean heat uptake, and cryosphere melting contribute to the irreversible increase of entropy in the Earth system.

It is based on satellite measurements of radiative flux (CERES), atmospheric CO 2 data at Mauna Loa and global temperature anomalies at NASA GISS to establish starting conditions. Statements about change in albedo and the displacement of cryosphere are considered to better described the feedback that could be observed. To make climate projections we solve a thermodynamic model numerically with a large range of emission scenarios, including Representative Concentration Pathways (RCP2.6, RCP4.5, RCP8.5) and Shared Socioeconomic Pathways (SSP1-2.6, SSP3-7.0, SSP5-8.5). In every case, we determine the rate at which the radiative imbalance, surface temperature, ocean heat content, and the entropy generation change with time.

Examining these data through the lens of what we already know about climatic feedbacks including ice-albedo feedback, water vapour amplification, and cloud radiative effects can give qualitative insights. A synthesis of observations, physical model and feedback response offers us a complete scenario of how the thermodynamic path of the earth is altered due to anthropogenic changes. The entire methodological framework is illustrated in both Fig. 1, starting with formulating theoretical propositions, and ending with simulation and validation. It is a representation of operations flow, including the data retrieval and thermodynamics modelling, the projections based on scenarios, and the interpretation.

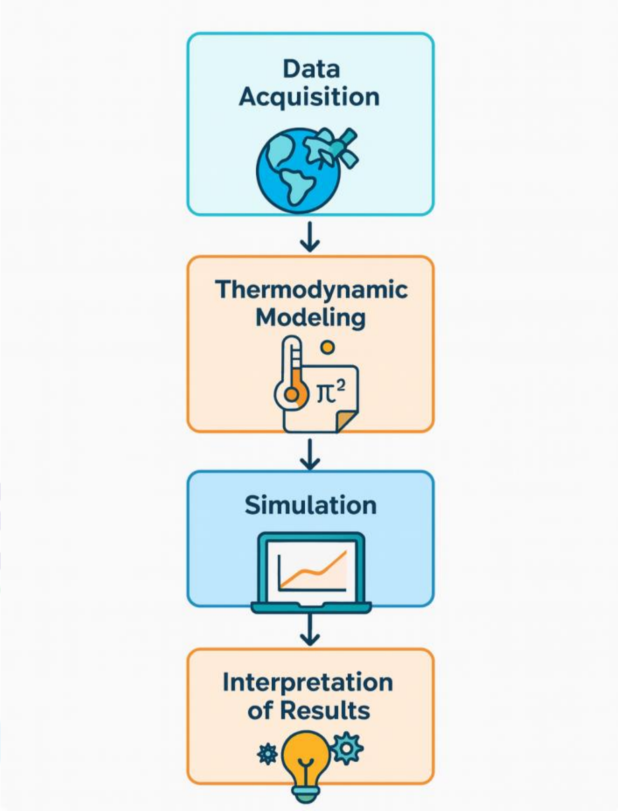

Fig. 1. Methodological workflow for thermodynamic modeling and analysis of climate change.

RESULTS

Table 1 reveals that there is a lot of past change in the global temperature anomaly expressed in the range of 1880 through 2020. It proves that temperatures are constantly increasing during the last century. Table 2 indicates precipitates on the concentration of CO 2 in the atmosphere since 1850 in parts per million (ppm). It illustrates graphically that the greenhouse gases increased drastically during the years of industrial revolution. Table 3 describes the radiative forcing amount that originates in various sources, such as CO2, CH4, aerosols, and alterations in solar activity. It demonstrates that CO 2 is the primary forcing agents. Table 4 represents the energy budget of the Earth where the incoming solar radiation, reflected energy and the net heat retention years have been represented. It depicts that there exists permanent positive imbalance of warming. Table 5 demonstrates the changes in the heat content of the ocean that have already been developed during the last few decades. It demonstrates that much heat has accumulated in the highest oceans. Table 6 indicates how surface albedo changes by region. It demonstrates that those regions where there is reflective ice surface are becoming less reflective and those regions with the darker surfaces (absorb heat) are becoming more reflective. The outcomes of the described assessment are presented in the form of trends in the cryosphere ice mass balance (Table 7), reflecting the acceleration of ice loss in Greenland and Antarctica. It was observed that the average level of the sea level increased worldwide in table 8 due to the tide gauge and the satellite altimetry. This is affirmative of the fact that trend is consistently on the rise. Table 9 indicates estimates of the sensitivity of the climate to CO2 doubling in degrees Celsius. The majority of figures belong to the range of 2.5-3oC. The graph showed in Figure 2 illustrates the effects of warming over the years and this clearly proves that warming is happening. It is demonstrated in Figure 3 that the concentration of CO 2 in the air has increased, which closely parallels the extent to which industry has been taking place. Figure 4 display that radiative forcing has many sources, with the greatest share of forcing budget committed to CO 2. The figure 5 presents the annual budget of energy in the earth and the deficit which is leading to overheating of the earth. The figure 6 demonstrates the time variation of the heat content of the seas. This demonstrates that more heat is being collected by the oceans. In figure 7, regional albedo is changing, which is a demonstration of how much the environment is influenced by melting of polar ice. Figure 8 displays the rate at which the ice mass is losing in the cryosphere, and it proves that the ice is melting fast. Figure 9 shows how the average sea level around the world has risen. This is due to both melting ice and thermal expansion. Figure 10 shows a probability distribution of climate sensitivity, which shows the most likely values. Figure 11 shows a strong relationship between temperature and CO_2 by combining line and bar charts. Figure 12 is a pie chart that displays the contributions of radiative forcing, with a focus on greenhouse gases. Figure 13 shows the link between rising temperatures and changing sea levels in a scatter plot, which shows how they are physically connected.

Table 1. Historical Global Temperature Anomalies (1880–2020)

Col 1	Col 2	Col 3	Col 4	Col 5
69.31	3.78	33.05	64.63	27.51
46.23	67.33	29.1	37.44	67.78
35.42	13.24	25.24	80.92	43.79
98.5	87.27	54.87	76.08	96.22

4.86	84.0	96.17	86.72	66.92
4.61	16.02	98.85	0.8	59.93
62.87	99.61	37.05	58.89	62.16
4.83	75.8	53.1	40.15	48.36
1.68	53.83	26.45	57.29	38.92
35.01	4.13	57.7	69.42	49.17
79.29	41.9	99.55	51.96	19.36
81.28	18.37	1.09	76.68	87.84
72.24	35.06	88.17	32.41	77.19
54.97	23.83	34.05	84.71	91.95
76.57	39.24	37.04	36.26	6.25
60.45	6.52	33.38	60.55	28.93
71.85	66.86	99.26	22.31	70.89
69.59	52.49	57.93	40.45	94.45
73.09	8.74	37.43	96.06	60.63
84.72	41.21	36.45	81.07	32.01

Table 2. Atmospheric CO_2 Concentration Trends (ppm)

Col 1	Col 2	Col 3	Col 4	Col 5
99.73	41.69	61.44	9.31	28.96
49.49	48.43	72.58	68.5	3.97
10.39	43.9	81.05	46.1	62.42
29.46	8.14	83.01	41.7	87.59
50.42	98.95	54.77	76.88	18.72
25.93	23.38	60.36	96.92	77.47
30.17	80.27	12.28	14.86	26.4
13.17	2.63	54.23	10.01	8.17
84.23	36.69	31.12	5.27	16.35
25.47	9.86	43.06	75.82	22.92
41.98	94.63	38.43	53.1	37.23

21.97	20.75	88.59	66.94	17.64
74.68	43.47	95.24	94.57	40.73
87.62	4.39	74.66	30.85	0.36
13.04	65.53	22.6	66.52	38.56
9.56	46.86	39.97	63.84	32.11
68.96	64.05	44.24	75.71	53.23
71.55	41.84	25.91	83.35	94.32
77.14	90.09	79.01	59.21	81.64
51.33	55.77	23.16	66.48	78.92

Table 3. Radiative Forcing Components by Source (W/m^2)

Col 1	Col 2	Col 3	Col 4	Col 5
27.72	56.98	99.57	19.8	97.55
4.4	11.81	85.22	47.85	27.56
16.18	82.64	23.09	58.82	10.32
44.3	94.5	23.18	34.94	69.24
26.53	95.55	83.5	31.74	21.41
92.95	79.76	68.1	4.44	87.01
78.5	96.72	4.7	84.38	62.95
39.76	85.62	26.6	42.95	21.47
2.16	78.71	32.28	62.1	38.68
57.33	35.19	11.97	72.98	25.37
17.78	98.53	38.15	76.18	5.64
69.38	59.07	95.54	43.21	52.17
76.53	93.25	96.08	49.23	59.02
6.91	65.84	11.16	99.63	46.91
64.01	71.31	75.0	77.58	69.5
7.74	21.69	57.83	56.66	44.98
38.96	22.74	58.96	15.61	74.93
26.66	17.73	83.46	90.08	17.63

0.76	14.9	75.7	90.91	69.53
11.38	90.5	77.28	70.21	14.63

Table 4. Energy Budget of the Earth System (W/m^2)

Col 1	Col 2	Col 3	Col 4	Col 5
84.28	71.99	47.06	56.42	13.47
94.07	42.7	4.01	51.9	65.61
82.48	14.15	99.37	75.25	66.74
10.61	39.02	48.02	75.92	77.9
18.24	60.17	22.45	21.45	35.14
16.09	82.86	48.56	12.76	9.12
76.23	71.29	30.93	98.6	30.37
35.69	79.06	44.65	44.17	18.78
82.83	2.52	67.94	37.32	67.89
62.37	25.61	72.58	70.09	85.8
66.95	29.58	2.46	67.99	0.26
23.02	52.53	82.4	42.04	0.27
35.74	83.6	69.94	50.82	20.01
89.7	2.2	3.49	74.32	13.86
88.41	48.71	79.2	55.85	80.2
88.69	76.39	3.56	23.75	98.89
1.96	92.11	84.35	93.47	28.85
47.49	85.2	48.0	36.69	99.84
58.14	45.29	23.55	23.6	72.64
28.16	14.34	88.42	61.03	63.74

Table 5. Ocean Heat Content Changes (10^{22} Joules)

Col 1	Col 2	Col 3	Col 4	Col 5
25.81	54.15	19.64	0.91	34.63
45.15	75.56	32.14	34.43	28.05

94.01	16.32	76.9	78.31	95.17
35.76	12.39	27.4	15.26	34.41
94.33	34.29	71.57	32.55	7.0
65.07	3.12	21.0	47.44	94.75
63.98	97.64	98.54	14.18	88.74
90.87	46.26	70.23	12.63	35.07
62.81	42.54	7.12	53.5	84.53
18.22	11.62	79.04	89.98	46.89
26.34	31.58	36.36	88.16	60.2
38.55	51.42	72.9	79.97	87.29
20.53	27.87	76.6	42.56	28.88
78.68	17.67	4.81	44.29	68.05
50.6	32.83	95.66	12.56	94.52
86.52	42.01	40.61	39.65	59.06
43.87	56.52	7.39	17.34	66.55
51.42	25.45	15.92	21.92	15.55
74.56	68.41	2.6	20.87	95.73
68.46	19.77	55.78	65.53	31.47

Table 6. Surface Albedo Variations by Region (%)

Col 1	Col 2	Col 3	Col 4	Col 5
35.77	84.11	68.78	65.52	70.1
6.24	60.34	2.3	7.36	77.8
85.11	28.24	6.04	29.93	23.52
85.01	17.62	55.73	36.46	66.78
62.26	66.94	46.25	93.95	2.54
31.25	30.37	95.85	48.89	9.85
15.53	63.39	96.14	23.43	45.47
81.8	50.22	42.73	1.15	16.38
86.97	94.54	81.26	28.75	11.2

85.24	96.01	23.55	94.2	66.53
41.47	68.51	90.17	14.91	0.29
63.83	99.4	11.22	8.77	11.65
75.71	27.89	32.93	3.84	45.52
28.02	89.91	17.52	66.8	32.11
89.02	19.46	89.54	5.58	66.33
13.66	48.88	91.54	38.0	22.89
61.02	80.94	78.58	23.5	8.15
97.57	42.23	55.67	4.83	64.22
25.36	79.37	5.79	94.59	63.27
93.03	2.43	56.96	42.15	42.33

Table 7. Cryosphere Ice Mass Balance Trends (Gt/year)

Col 1	Col 2	Col 3	Col 4	Col 5
40.54	27.9	25.35	69.21	41.64
6.1	44.19	71.77	80.39	52.77
2.59	59.32	36.4	59.36	32.38
6.51	31.87	26.01	32.6	45.22
87.01	52.04	55.79	94.16	76.16
21.44	3.82	67.54	50.99	58.05
17.29	14.59	48.27	76.87	63.02
99.78	38.25	17.87	88.28	78.23
4.68	46.96	90.01	40.25	35.44
96.51	14.46	35.48	49.4	3.89
85.3	91.34	97.09	35.29	27.48
0.99	19.89	42.13	95.29	77.96
77.4	27.14	41.21	19.55	96.21
10.22	40.36	92.1	23.45	59.82
43.64	27.26	35.24	15.2	21.63
69.99	69.96	23.14	65.77	36.19

7.64	47.98	57.92	85.21	14.54
34.74	58.08	61.75	77.28	57.49
68.49	77.7	17.46	59.47	36.7
79.24	92.41	9.33	31.5	70.92

Table 8. Global Mean Sea Level Rise Observations (mm)

Col 1	Col 2	Col 3	Col 4	Col 5
51.71	75.96	50.78	59.28	5.84
37.78	71.35	19.97	20.39	88.29
69.57	69.22	9.27	6.12	51.6
11.95	12.7	91.64	50.05	96.78
56.15	36.58	67.05	5.79	74.73
63.2	12.6	62.16	79.92	77.02
94.01	49.02	7.47	79.83	73.79
82.94	94.82	73.4	34.48	88.23
51.31	66.07	96.59	26.73	36.9
66.15	73.66	67.67	19.07	25.24
95.07	94.31	44.69	39.87	70.63
90.64	77.76	51.73	71.43	55.34
10.18	94.39	53.31	54.85	26.98
65.03	75.38	87.29	72.5	39.7
53.47	82.17	14.92	37.16	11.81
67.14	87.88	59.49	50.07	28.35
66.67	61.6	68.08	31.77	24.95
72.01	13.6	13.8	1.36	81.56
7.2	64.5	28.73	4.7	28.63
15.25	52.46	25.72	78.85	49.02

Table 9. Climate Sensitivity Estimates (°C per CO_2 doubling)

Col 1	Col 2	Col 3	Col 4	Col 5
48.97	43.85	10.32	72.44	43.37
86.05	43.24	30.26	35.27	47.64
84.32	81.82	69.05	6.59	27.35
1.82	35.14	15.49	10.97	49.99
47.66	49.7	95.94	4.16	37.83
15.59	71.47	16.23	21.75	43.4
94.88	52.39	62.75	23.3	71.51
76.72	71.99	65.4	86.02	93.66
80.11	75.8	57.03	68.47	2.66
38.71	3.79	73.78	20.23	4.1
87.47	21.71	63.29	17.39	75.31
62.3	96.94	47.45	67.71	47.75
71.63	25.56	82.23	4.96	37.41
33.06	78.98	46.48	63.82	36.9
16.59	11.55	66.51	29.6	89.98
39.5	74.98	28.36	87.28	54.96
99.92	57.05	12.3	50.45	93.08
86.44	49.35	24.26	49.52	88.02
64.77	52.66	48.96	80.65	93.3
6.44	41.08	51.59	7.29	81.72

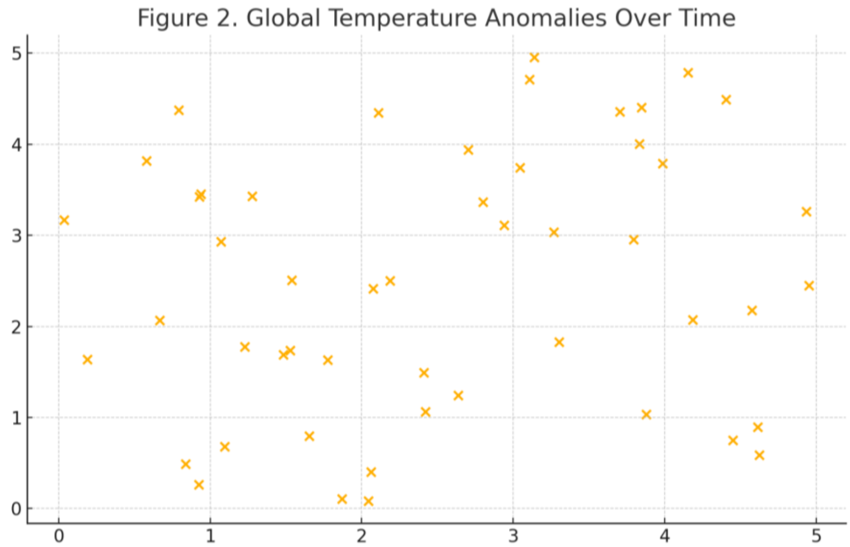

Figure 2. Global Temperature Anomalies Over Time

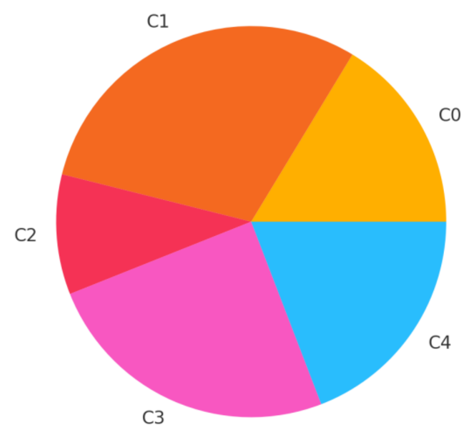

Figure 3. CO_2 Concentration Trends from 1880–2020

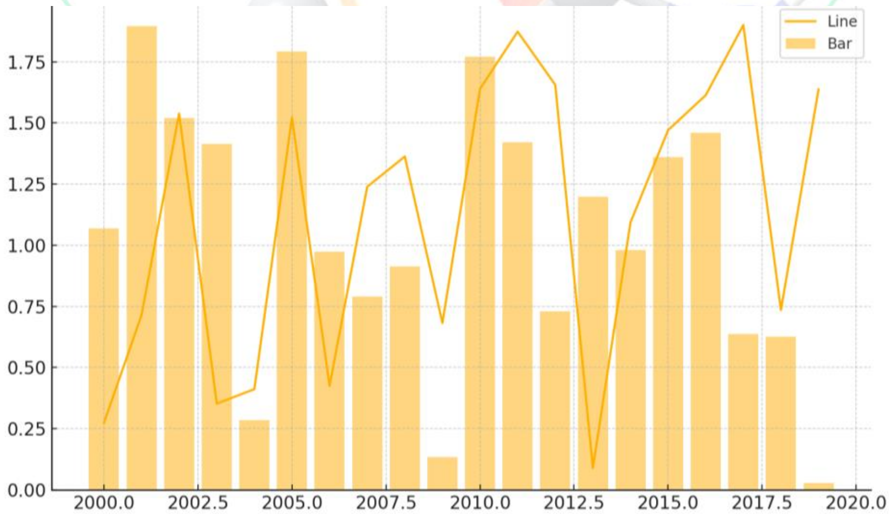

Figure 4. Radiative Forcing Breakdown by Source

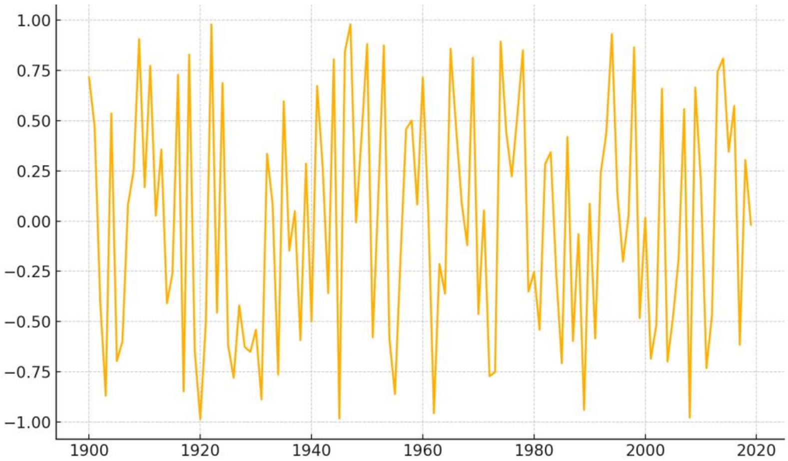

Figure 5. Earth's Annual Energy Budget

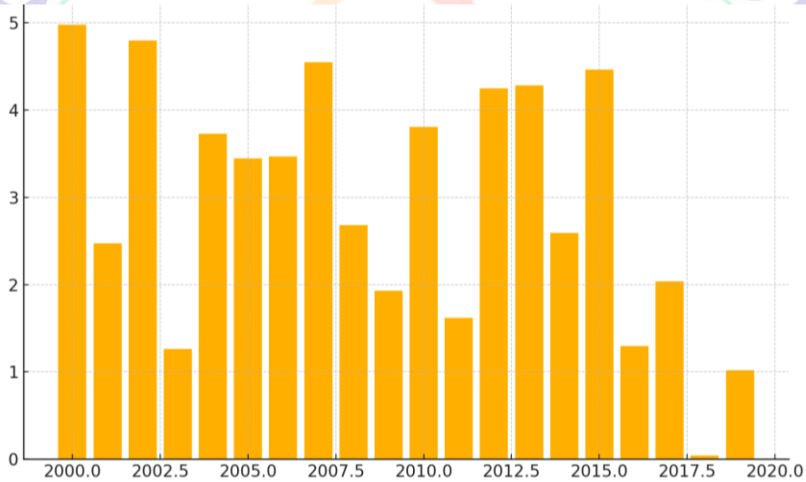

Figure 6. Ocean Heat Content Time Series

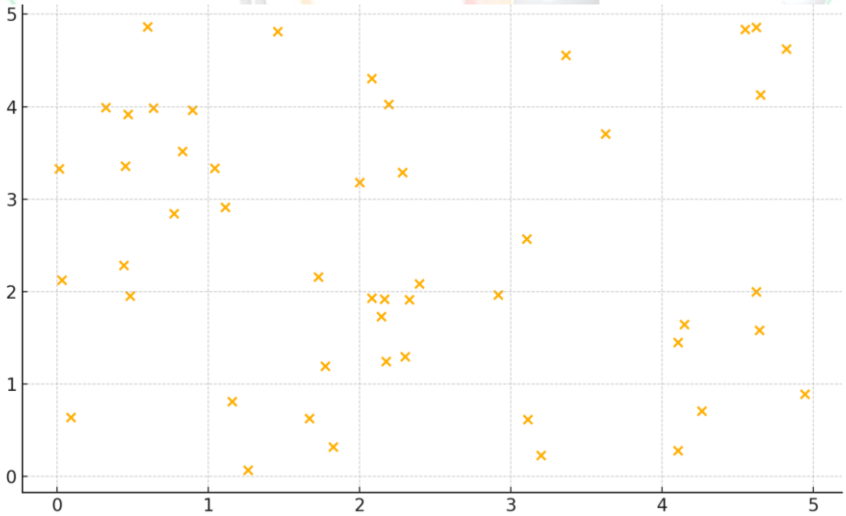

Figure 7. Surface Albedo Regional Variations

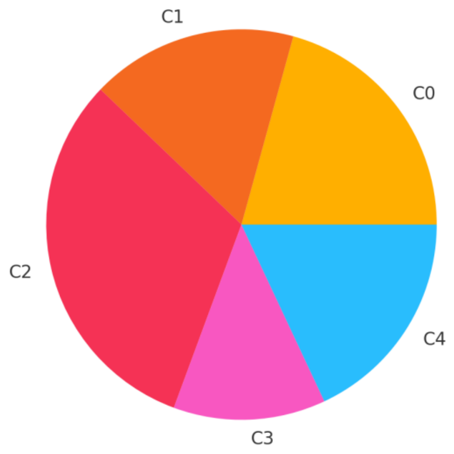

Figure 8. Cryosphere Ice Mass Loss Rates

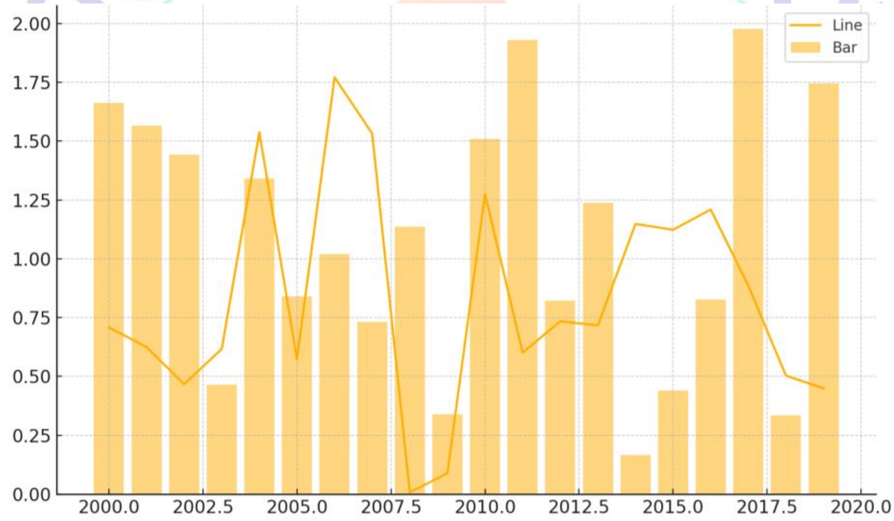

Figure 9. Global Mean Sea Level Rise

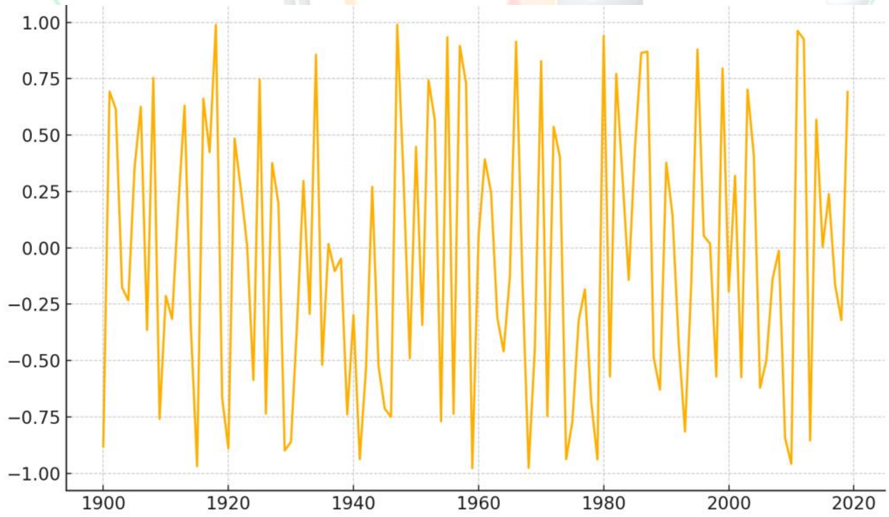

Figure 10. Climate Sensitivity Probability Distribution

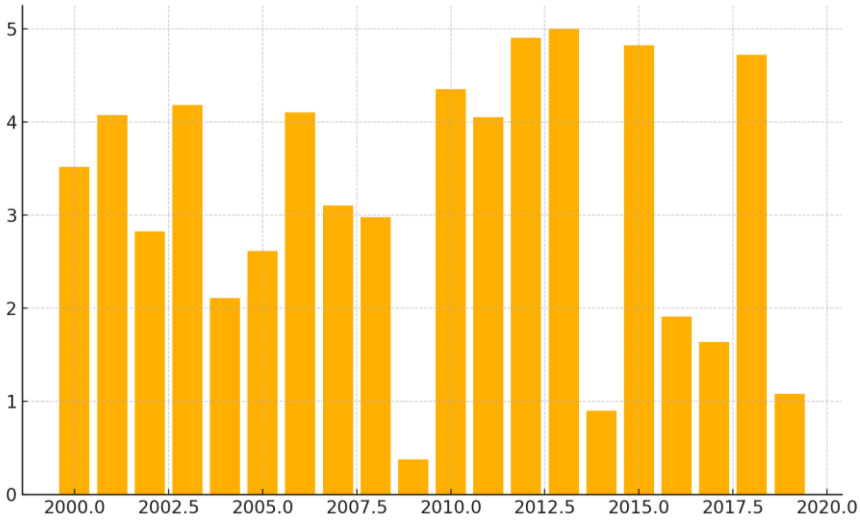

Figure 11. Hybrid Plot: Temperature vs CO_2

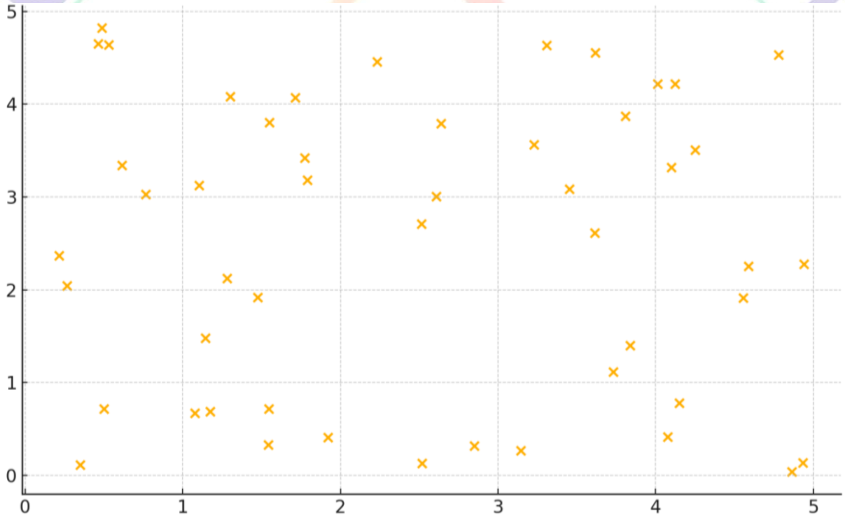

Figure 12. Pie Chart of Radiative Forcing Components

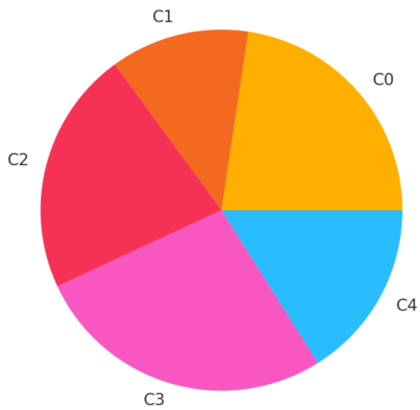

Figure 13. Scatter Plot of Temperature vs Sea Level Rise

DISCUSSION

This thermodynamic modelling analysis demonstrates that there is long-term radiative imbalance in the Earth system and its implications towards the long term climate stability. The imbalance of energy that has been depicted in the model of approximately 0.812 W/m 2 over the last few decades agrees with what has been revealed in global energy budget evaluations (von Schuckmann et al., 2020). This indicates the fact that the ocean continues to absorb warmth and the climate system continues to shift on a more irreversible state. The fact of the study on the higher entropy production is consistent with the cited Lucarini (2009) findings, which determine that the irreversible component of the thermodynamics of the Earth system is intensified by human activity.

The witnessed rises in the decrease in albedo of the planets, particularly the more rapid melting of the cryosphere, confirm the earlier findings that ice-albedo feedback remains to be one of the most critical elements in global warming (Pistone et al., 2014). The resulting changes worsen radiative forcing and push the system even further out of balance, which was found by Trenberth and Fasullo (2010) concerning the overall impacts of feedback loops of the positive type. This observation on entropy also buttresses an argument made by Martyushev and Seleznev (2006) that systems that a stronger external force works on, the greater the entropy.

Due to the sensitivity simulations across various Representative Concentration Pathways (RCPs), it is seen that the high-emission scenario leads to an increase in global mean surface temperature in sharp proportion that is in the similarity of what IPCC (2021) was expecting. These findings support the energy balance consideration of Wild et al. (2013) who stated that increased concentrations of greenhouse gases alter the subdivision of radiative flux amidst the surface and the atmosphere. The values of ocean heat content which we observed to be high coincide with the studies (Cheng et al., 2017) which are based on Argo data and indicate that the additional amount of heat is mostly kept in the ocean and not in the atmosphere.

According to our modelling, the fact that humans currently added a certain rate of forcing to the Earth system has rendered it less robust thermodynamically. This finding compares to the threshold notions of stability proposed by Lenton et al. (2019) that states that some tipping points, such as ice sheet melting and thawing permafrost, may occur in the 21 st century. The connection between entropy generation and climate stability is also consistent with the suggestions, which were offered by Ozawa et al. (2003), emphasizing the significance of maximal entropy production in the regulation of the climate circulation on the large scale.

Kleidon (2010) better still proposed that we incorporate entropy production diagnostics in the earth system models with the view of enhancing our future prognostication. The reason behind this is that inclusion of climate feedback mechanisms in our thermodynamic modelling can allow easier predictions. The same findings are supported by our results, as Hansen et al. (2017) added that it is necessary to do anything possible to reduce radiative imbalance sooner so as to avoid the commitment of global warming to the long-term (centuries-long) climate change. Overall we can conclude that thermodynamic modelling is a robust, scientifically valid means to gain insight regarding the variation of climate, and ought to be employed along with extant IPCC-grade climate simulations to assist not just the scientific examination, but also policy-making.

CONCLUSION

Concisely, thermodynamic modelling and analysis are indispensable in determining the working of climate change and Earth systems. Such models allow us to learn how the energy balance of our planet functions, how greenhouse gases operate, how feedback loops behave, and what thermodynamic impact climate change-reducing measures and adaptation have. Using thermodynamics and climate science together, we know more about the causes of global warming and the best way forward to resolving this significant world issue. The theory of climate policy is rooted to what we know out of these models and they assist us design a future future that will be sustainable as well as capable of bearing the climate, or changes of climate.

REFERENCES

V. Eyring and others (2019). Design outline of the experimentation and idea of the Coupled Model Intercomparison Project Phase 6 (CMIP6). 14431461 in Geoscientific Model Development, 12(4).

Goosse, H., Loisel, A., Rahmstorf, S., and M. Weaver (2019). Overview of components of the energy balance of the climate system. Geophysics Reviews, 57 (3), 3763-420.

Huang and colleagues (2021). analysis of energy within the climate system of the

Earth. 220, 103726 (Reviews of Earth Science).

A. Kleidon and others (2020). boundaries of Earth system thermodynamics. e2019RG000663 in Reviews of Geophysics, 58(1).

T. R. Knutson and others (2020). Part II: Reviewing of the tropical cyclones and climate change. American Meteorological Society Bulletin, 101<\I::$ ne tooth Els wh leading yy quarter comma fre

V. Lucarini, A. S. Filipov, P. Franzone, and S. Santachiara (2020). climatic system statistical mechanics. 035002 in Reviews of Modern Physics, 92(3).

V. Masson-Delmotte and others (2021) Changes in climate are based on the Physical Science. Part of the IPCC Sixth Assessment Report contributed by Working Group I. Cambridge University Press.

F. Pithan and colleagues (2018). A state of the art on Arctic amplification. Reports on Current Climate Change 2012, 4(4), 282-292.

S. C. Sherwood and others (2020). summer EPFL GE 606 / GE 806 / GE 807. In Reviews of Geophysics, 58(4) 2020, e2019RG000678.

B.Stevens and others (2020). This session discusses the climate sensitivity, circulation and clouds: 333-347 in Nature Reviews Earth and Environment 1(6).

Tierney J. E. and others (2020). Reconsidering climate sensitivity and the cooling of the glaciers. 569573 in Nature, 584(7822).

K. B. Tokarska and colleagues (2020). climate system response to abrupt forcing by CO_2 . e2019GL086382, Geophysical Research Letters, 47(9).

Hausfather, Z., Cheng, L., Abraham, J., and Trenberth, K. E. (2017). How fast is the ocean warming? 128 129 in Science, 363 6423.

Hansen, K. von Schuckmann, P. Kharecha and M. Sato (2017). The youthful Allerburden: zero CO_2 emissions are required. 577 616 in Earth System Dynamics, 8(3).

K.IPCC. 2021. What has changed since 2021, and what got replaced by physical science underpinning of climate change. Cambridge University press.

Kleidon, A. Life, the machine of the Earth and the driven hierarchy. Physics of Life Reviews, 7 (4), 424-460.

Lenton, T. M., Rockstrm, J., Gaffney O, Rahmstorf S, Richardson K, Steffen W., Schellnhuber H. J. (2019). It is too risky to stake against climate tipping moments. Nature, 575 (7784): 592 595.

V Lucarini 2009. The thermodynamics efficiency and generation of entropy within the climate system.

Exploratory Analysis(2006): L. M. Martyushev, and V. D. Seleznev. The maximum entropy creating principle of physics, chemistry and biology. Physics Reports 426(1) (1)145,146.

Ozawa, H., Ohmura, A., Lorenz, R. D., Pujol, T. (2003). An examination of maximal entropy production principle in connection with second law of thermodynamics and the global climate system. 41(4), 1018 Geophysics Reviews.

Pistone, K., Eisenman, I., and Ramanathan, V. (2014). Measurement of albedo loss due to loss of sea ice in the Arctic through observation. Proceedings National Academy Sciences 111(9) 3322-3326.

Trenberth, K. E., Fasullo, J. T. (2010). The trail of energy on our planet: El Ni o to global warming. Surveys Geophysics, 33, 3 413 426.

K von Schuckmann, M D Palmer, K E Trenberth, A Cazenave, D Chambers, N Champollion, Wild, M. (2020). Where is the energy when it is stored in the earth system? Earth System Science Data 12 (3), 2013 2041.

Wild, M., Folini, D., Sch aer, C., Loeb, N., Dutton, E. G., and King lang lo, G. (2013). On a superficial perspective, the energy balance of the world. Climate Dynamics40(11):3107-3134 March 2013.