Aspects of Negative Entropy Flow in Cyclones: From Classical to Quantum

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Abstract:
The study focuses on exploring the concept of negative entropy flow in cyclones and investigates the potential of applying quantum-inspired approaches to better understand and estimate the negentropy of these complex systems. By incorporating principles from quantum mechanics, such as the second law of thermodynamics and Gibbs energy, we aim to improve the accuracy of entropy predictions for cyclones. Classical methods for estimating entropy flow, such as Shannon entropy and von Neumann entropy, are examined, along with their limitations in capturing the complex dynamics of cyclonic systems. Additionally, the project utilizes the simulated annealing optimization method to explore the quantum aspects of entropy flow in cyclones. The objective is to provide insights into the negentropy of cyclones and its potential applications in weather forecasting. This project analyses data from two recent cyclones "Mocha" and "Biporjoy" and estimates their negentropy using the developed quantum-inspired algorithms. The findings contribute to a deeper understanding of the entropy dynamics in cyclones and showcase the potential of quantum-inspired techniques in weather forecasting and related fields.

Keywords: Negentropy, Entropy estimation, Gibbs energy, Simulated annealing, Cyclones, Optimization techniques, Quantum-enhanced models.

1. Introduction

Entropy is a fundamental concept in physics and information theory that quantifies the amount of disorder or uncertainty in a system. In classical thermodynamics, the second law states that the entropy of an isolated system tends to increase over time, leading to a loss of useful energy. However, in the realm of quantum information theory, negative entropy, also known as negentropy, emerges as a significant concept with profound implications. Cerf and Adami (Kellogg Radiation Laboratory, California Institute of Technology) have extensively studied negative entropy in the context of quantum information theory [1]. Their work explores how quantum systems can exhibit negative entropy, indicating the presence of highly ordered and structured information. In a different domain, Liu and Liu (Chinese Academy of Meteorological Sciences, Beijing) investigate the role of negative entropy flow in synoptic-scale severe atmospheric systems [2]. By analysing the negentropy flow within these systems, they aim to gain insights into their dynamic behaviour and improve our understanding of atmospheric processes. In the realm of many-body quantum systems, Quarati, Lissia, and Scarfone investigate negentropy and its implications [3]. They explore how negentropy manifests in complex quantum systems comprising numerous interacting particles. Lastly, the work of Liu and Liu explores the entropy flow and evolution of storms

[4]. By investigating the negentropy flow within storm systems, they seek to uncover the underlying mechanisms driving storm development, intensity changes, and eventual dissipation.

2. Negative Entropy Flow in Classical Dynamics:

The concept of negative entropy flow extends beyond the realm of quantum information theory and finds relevance in classical dynamics, particularly in the study of synoptic-scale severe atmospheric systems and storm evolution. Liu and Liu have explored the effect of negative entropy flow on the organization of such systems [2][4]. Their research delves into the intricate dynamics of cyclones and storms, investigating how the flow of negative entropy plays a crucial role in shaping their behaviour.

In synoptic-scale severe atmospheric systems, negative entropy flow manifests as the transfer of highly ordered and structured information within the system. This flow contributes to the organization and development of cyclones, influencing their intensity, structure, and longevity. By analysing the negentropy flow, Liu and Liu aim to unravel the underlying mechanisms driving the organization and evolution of these atmospheric phenomena.

During the development phase of a cyclone, negative entropy flow facilitates the aggregation and convergence of air masses, leading to the formation of a well-defined low-pressure centre. The flow of negentropy sustains the circulation of warm and moist air towards the core of the cyclone, fueling its intensification. This process involves the exchange of heat, moisture, and momentum, which further enhances the organization and complexity of the system. As a cyclone reaches its mature stage, the negative entropy flow continues to drive the intricate interactions between the various atmospheric components. It influences the formation and maintenance of features such as eyewalls, rainbands, and outflow channels, which are critical to the cyclone's structure and intensity. The negative entropy flow also influences the vertical distribution of atmospheric variables, such as temperature, humidity, and wind speed, contributing to the overall stability and dynamics of the cyclone. While negative entropy flow promotes the organization and complexity of cyclones, it eventually gives way to the dissipation phase. As a cyclone interacts with its surrounding environment and loses its source of energy, the negative entropy flow diminishes, leading to the gradual decay and dissipation of the cyclonic system.

2.1 Second law of Thermodynamics and Gibbs Relation:

The concept of negative entropy flow in cyclones has been extensively studied by Liu and Liu in their papers [2] and [4]. They present a comprehensive analysis of the effect of negative entropy flow on the organization and evolution of synoptic-scale severe atmospheric systems.

To understand the concept of negative entropy flow in cyclones, we can start with the Gibbs relation and the second law of thermodynamics. The Gibbs relation for the total differential of the entropy per unit mass can be written as:

$$T\delta s = C_v \delta T + p\delta\alpha - \sum_r \mu_r \delta N_r \qquad (1)$$

In Equation (1), s represents the specific entropy, T is the temperature, p is the pressure, C_v is the specific heat at constant volume, $\delta\alpha$ is the specific volume, μ_r is the chemical potential for component r, and Nr is the fractional mass for component r.

For the atmospheric system under consideration, where the atmosphere can be treated as a mixture of ideal gases, the specific entropy s can be expressed as:

$$s = \sum_r N_r s_r \qquad (2)$$

In Equation (2), s_r is the specific entropy for the rth ideal gas, which can be calculated using the specific heat at constant pressure (C_{pr}), gas constant (R_r), partial pressure (p_r), and entropy constant (s_{r0}) for component r.
Next, assuming no diffusive flows in the system, the diffusion flow J_r for component r can be defined as $\vec{J_r} == p_r(\vec{v_r} - \vec{v})$, where ρr is the density of component r, V is the velocity for the mass center, and V_r is the velocity for component r.
Using these definitions and applying the continuity equation and the mass conservative equation, the entropy balance equation for the mixed ideal gases in quasi-Lagrangian coordinates can be derived as:

$$\frac{\partial ps}{\partial t} = -\nabla.(ps\vec{V} + \frac{1}{T}\vec{J}q - \sum_k \frac{\mu_k}{T}\vec{J}k) + \sigma \qquad (3)$$

In Equation (3), $\frac{\partial ps}{\partial t}$ represents the quasi-Lagrangian change rate of specific entropy, σ is the entropy production, and ∇· represents the divergence operator.

To calculate the entropy budget of the system, the entropy balance equation (3) can be integrated over the entire volume (V) to obtain:

$$\frac{\partial s}{\partial t} = \int\int\int_V \frac{\partial ps}{\partial t} dV = \int\int\int_V (-\nabla.(ps\vec{V} + \frac{1}{T}\vec{J}q \sum_k \frac{\mu_k}{T}\vec{J}k) \ \ \sigma) \ \ d\Sigma(-\frac{\partial p}{pg}) \qquad (4)$$

In Equation (4), S denotes the total entropy of the system, X represents the spatial coordinates, p is the pressure, p is the density, and g is the gravitational acceleration.

By applying the Gibbs relation (Equation 1) and the entropy balance equation (Equation 4), it is possible to derive the formula for the negative entropy flow and estimate its effect on the organization of synoptic-scale severe atmospheric systems. The specific entropy (s) in a cyclone can be expressed as the sum of two components: the entropy of vapor (sq) and the entropy of dry air (sd) as given in [2],[4].

$$s = sq + sd = q(C_{pv} \ln T - R_v \ln e) + (1 - q)(C_{pd} \ln T - R_d \ln(p-e)) \qquad (5)$$

In Equation (5), q represents the specific humidity, T is the temperature, e is the vapor pressure, C_{pv} and R_v are the specific heat at constant pressure and the gas constant for vapor, respectively. Similarly, C_{pd} and R_d are the specific heat at constant pressure and the gas constant for dry air, respectively.

Now, we will use these equations to study two cases of cyclones and their structures.

2.2 Case Study of Cyclones:

We considered two of the recent cyclones "Mocha" which was originated in Indian Ocean and Bay of Bengal and affected North-eastern states of India, Bangladesh and Myanmar and cyclone "Biporjoy" originated in Arabian Sea and affected mostly Pakistan and India.

2.2.1 Cyclone Mocha:

Cyclone Mocha is a powerful and intense tropical cyclone that exhibits significant strength and destructive potential. With wind speeds reaching up to 250 km/h, it is classified as a very severe cyclonic storm and the temperature for running waters was greater than 30°C [5]. The cyclone has a well-defined circulation centre and is characterized by a low-level vorticity of approximately $300 \times 10^{-6}\ s^{-1}$ to the south of its centre and has 850 hPa and 200 hPa for vertical extension. Mocha is associated with extensive cloud cover, including broken to solid cloud distribution, indicating a high concentration of moisture in the atmosphere. The cloud intensity varies from weak to intense, with cloud top temperatures ranging from above -25°C to below -70°C [5]. These extreme cloud temperatures suggest the presence of deep convection and intense thunderstorm activity within the cyclone. Mocha poses a significant threat in terms of its potential to cause heavy rainfall, strong winds, and storm surges, leading to severe damage and disruptions in the affected regions [7]. The probability of cyclone genesis or formation is high, indicating a high likelihood of Mocha evolving into a tropical depression.

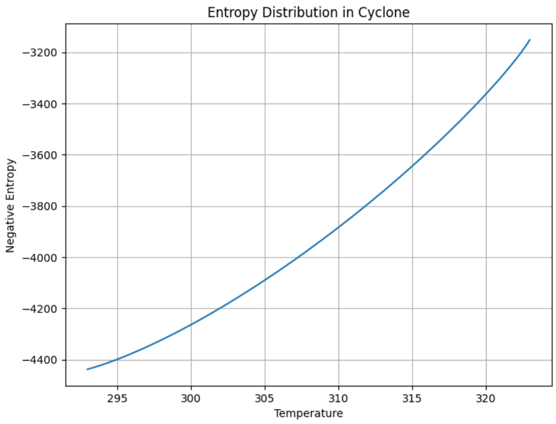
The parameters such as specific heat at constant pressure for vapor (C_{pv}), gas constant for vapor (R_v) remain constant for water vapor and do not change significantly based on the cyclone's strength and specific heat at constant pressure for dry air (C_{pd}), and gas constant for dry air (R_d) also remain constant for dry air and are not directly influenced by the cyclone's intensity. From equation (5),

$$C_{pv} = 1000\ , R_v = 461\ , C_{pd} = 1005\ , R_d = 287$$

As Mocha has greater cyclone strength than Biporjoy so we reduced the cyclone pressure to 300 hpa and took higher temperature around 50°C or 323K for maximum limit and this was our result;

Temperature: 323, Pressure: 300, Negative Entropy: -3151.5715669675296

Fig 1. Entropy distribution of Mocha



And we took a greater radius for cyclone Mocha than the average radius.

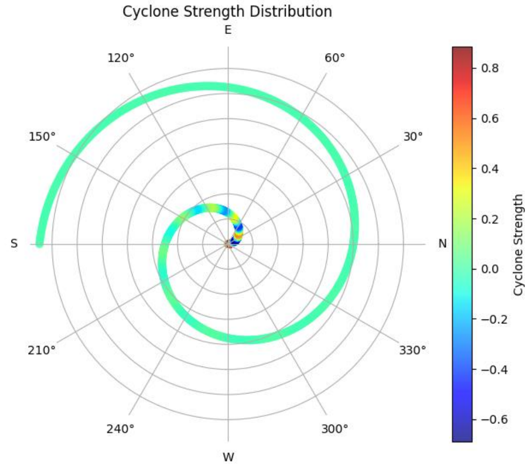


Fig 2. Cyclone Strength Distribution in Mocha

2.2.2 Cyclone Biporjoy:

Cyclone Biporjoy is a moderately strong tropical cyclone characterized by its wind speeds of approximately 140 km/h [6]. While not as intense as Cyclone Mocha, Biporjoy still possesses considerable power and can cause significant impacts. The cyclone exhibits a lower wind speed compared to Mocha, indicating a relatively weaker intensity. The minimum cloud top temperature recorded is -93°C [6]. The maximum sustained wind speed associated with the depression is 25 knots, gusting up to 35 knots. The estimated central pressure is 994 hPa and a mean sea level pressure (MSLP) of 993.6 hPa [6]. Regarding the atmospheric conditions, the low-level vorticity is around 200-250x10^{-6} s^{-1} and is located near the centre of the system. It is associated with a moderate level of cloud cover, with scattered cloud distribution. The convection intensity of Biporjoy ranges from weak to moderate, with cloud top temperatures ranging from -25°C to -40°C. These temperatures suggest the presence of convective activity and the potential for moderate thunderstorms within the cyclone. While Biporjoy may not reach the extreme destructive potential of Mocha, it can still bring about strong winds, heavy rainfall, and potential disruptions in the affected regions.

C_{pv} = 1000 ,R_v = 461 ,C_{pd} = 1005 ,R_d = 287 as the unchanged parameters in calculating the negative entropy.

For Biporjoy so we took higher cyclone pressure to 900 hpa and took lower temperature around 30°C or 303K for maximum limit and this was our result;

Temperature: 303.0, Pressure: 900.0, Negative Entropy: -3443.15854156927

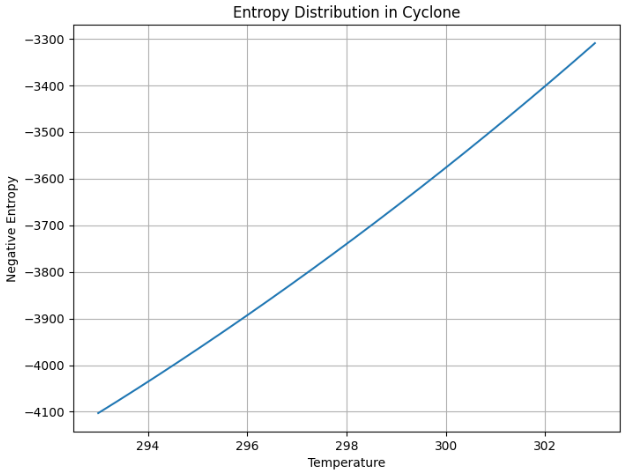


Fig 3. Entropy distribution of Biporjoy

We took the radius for Biporjoy smaller than Mocha.

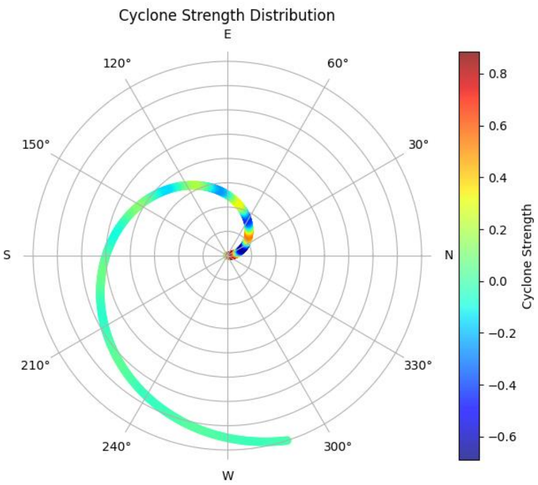


Fig 4. Cyclone Strength Distribution in Biporjoy

3. Understanding Negentropy in Quantum Aspects:

Negentropy, often referred to as negative entropy, refers to the reduction or reversal of entropy, indicating a state of increased order or information content. Studying negentropy in quantum systems involves investigating phenomena such as quantum coherence, entanglement, and quantum information processing, where information can be manipulated and transferred with high efficiency.

3.1 Boltzmann Gibbs Shannon entropy and Von-Neumann entropy:

Shannon's Gibbs formula is used to calculate the entropy of a classical information source. It is derived based on the principles of information theory. The formula for entropy, denoted as H(X), is given by [1]:

$$H(X) = -\sum[P(x) \log(P(x))] \qquad (6)$$

where P(x) is the probability of occurrence of each symbol x in the source.

The derivation involves considering the properties of a good measure of uncertainty or information content. It is assumed that the measure should satisfy certain desirable properties, such as being continuous, increasing with the number of equally probable outcomes, and being additive for independent sources. By exploring these properties, it is possible to arrive at the expression for entropy as shown above.

On the other hand, von Neumann entropy is used to quantify the entropy or information content in quantum systems. The formula for negative entropy (negentropy) in quantum information theory is given by [1]:

$$N = S - S_{min} \quad (7)$$

where:
N is the negative entropy,
S is the entropy of the quantum system, and
S_min is the minimum possible entropy It is derived based on the principles of quantum mechanics. The formula for von Neumann entropy, denoted as $S(\rho)$, is given by [1],[3]:

$$S(\rho) = -\mathrm{Tr}(\rho \log(\rho)) \quad (8)$$

where ρ is the density matrix representing the quantum state of the system.

The derivation of von Neumann entropy involves considering the properties of quantum states, density matrices, and the concept of mixed states. It is derived using the properties of the density matrix and the von Neumann entropy is found to be a measure of the purity or mixedness of a quantum state. The formula can be understood as an extension of Shannon's entropy to the quantum domain.

In quantum mechanics, the density matrix is a mathematical representation of the state of a quantum system. It is typically used to describe the statistical mixture of different quantum states and their probabilities. The density matrix formalism is not applicable to classical systems like cyclones or storms. Cyclones and storms are macroscopic weather phenomena governed by classical physics, specifically fluid dynamics and thermodynamics. However, quantum computing has the potential to help improve weather forecasting in a few ways. This includes optimization problems, which are used in various aspects of weather forecasting, such as data assimilation, numerical weather prediction, and ensemble forecasting. In the next part we will focus on the optimization technique such as Quantum annealing.

3.2 Computational method: Stimulated Quantum Annealing:

Quantum annealing is a computational approach that leverages the principles of quantum mechanics to solve optimization problems. It is a specific type of quantum computing architecture and algorithm that aims to find the lowest-energy state (global minimum) of a given objective function.
Here is a brief explanation of quantum annealing and how it is used [8]:

Objective Function: The first step is to define the problem as an objective function. The objective function represents the optimization problem that needs to be solved. It can be formulated as finding the configuration of variables that minimizes or maximizes the function.

Qubits and Ising Model: Quantum annealing systems, such as those based on superconducting qubits, represent the problem using qubits. The qubits are arranged in a network, and the problem is mapped onto an Ising model or a related formulation. The Ising model represents the interactions and constraints of the problem using binary variables.

Quantum Annealing Process: The quantum annealing process involves gradually evolving the quantum system from an initial state to a final state that encodes the solution to the optimization problem. This evolution is driven by the time-dependent Hamiltonian of the system.

Annealing Schedule: The annealing schedule determines how the Hamiltonian changes over time during the annealing process. Initially, the system is prepared in a simple Hamiltonian that is easy to prepare and control. Then, the system is slowly transformed to the Hamiltonian that represents the objective function to be optimized.

Quantum Fluctuations and Tunneling: During the annealing process, the quantum system undergoes quantum fluctuations and tunneling, allowing it to explore different configurations of the variables. This exploration helps the system search for the optimal solution by effectively traversing the energy landscape of the objective function.

Measurement and Result Extraction: After the annealing process, the final state of the qubits is measured to extract the solution. The measurement provides a set of classical bit strings that represent the values of the variables, which correspond to a potential solution to the optimization problem.

Post-processing and Analysis: The output of the quantum annealing process may need further post-processing and analysis. This could involve filtering and refining the obtained solutions, assessing their quality, and verifying their correctness.

Now, we will implement the simulated annealing algorithm in a programming language which would involve translating the pseudocode into actual code and incorporating any additional logic specific to the problem.
Also we know that stronger cyclones tends to have higher disordered states so they have less negative entropy as compared to the average cyclones.
Next, we will compute the negative entropy of Mocha and Biporjoy by using the Simulated Quantum Annealing
method.
The initial parameters are temperature and cooling rate and for the medium to strong cyclones we increase the initial temperature and decrease the cooling rate and for medium-low cyclones we decrease the temperature and increase the cooling rate [9].

3.2.1 Cyclone Mocha:

We considered initial temperature as 200K and cooling rate as 0.89

Best Solution:

[1 1 1 0 1 0 1 1 1 1 0 1 0 1 1 1 0 1 1 0 1 1 0 1 1 1 1 0 1 1 0 1 0 0 0 0 1 1 0 1 0 1 1 0 0 1 1 1 0 1 0 1 0 0 1 0 1 0 1 1 1 0 1 1 1 0 1 1 1 0 0 1 0 1 0 0 1 1 0 0 1 0 1 1 0 1 0 1 0 0 1 1 0 1 0 1 1 1 1 0]

Negative Entropy Flow:

[1 2 3 3 4 4 5 6 7 8 8 9 9 10 11 12 12 13 14 14 15 16 16 17 18 19 20 20 21 22 22 23 23 23 23 23 24 25 25 26 26 27 28 28 28 29 30 31 31 32 32 33 33 33 34 34 35 35 36 37 38 38 39 40 41 41 42 43 44 44 44 45 45 46 46 46 47 48 48 48 49 49 50 51 51 52 52 53 53 53 54 55 55 56 56 57 58 59 60 60]

Sum of the Entropy Flow: - 3164

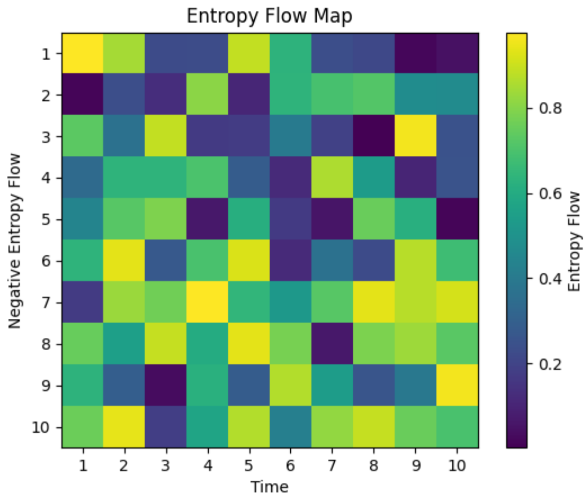


Fig 5. Negative Entropy Flow In Mocha

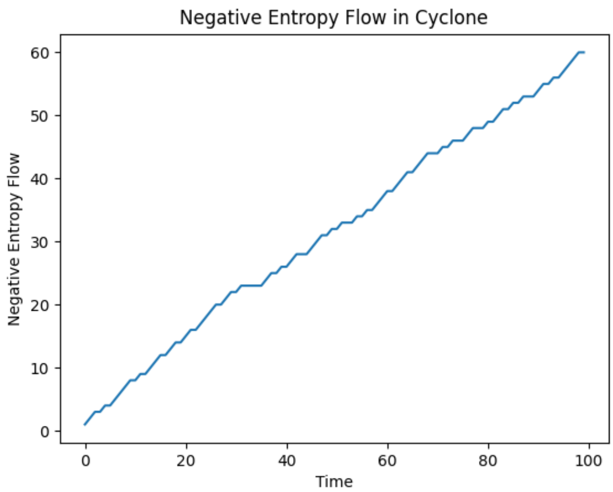


Fig 6. Entropy Flow Distribution in Mocha

3.2.2 Cyclone Biporjoy:
We considered initial temperature as 170K and cooling rate as 0.99
Best Solution:
[1 1 1 0 1 1 0 1 1 1 0 1 0 1 0 1 0 1 1 0 1 1 1 0 1 0 1 1 1 1 0 1 1 1 1 0 1 1 0 1 1 1 0 1 1 0 1 1 0 1 1 0 0 0 1 1 1 0 0 1 1 0 0 1 1 1 1 0 1 1 1 1 1 1 1 1 1 0 0 0 1 0 0 0 1 0 0 1 1 1 1 1 1 1 0 0 0 1 1 0]
Negative Entropy Flow:
[1 2 3 3 4 5 5 6 7 8 8 9 9 10 10 11 11 12 13 13 14 15 16 16 17 17 18 19 20 21 21 22 23 24 25 25 26 27 27 28 29 30 30 31 32 32 33 34 34 35 36 36 36 36 37 38 39 39 39 40 41 41 41 42 43 44 45 45 46 47 48 49 50 51 52 53 54 54 54 54 55 55 55 55 56 56 56 57 58 59 60 61 62 63 63 63 63 64 65 65]

Sum of the Entropy Flow: - 3412

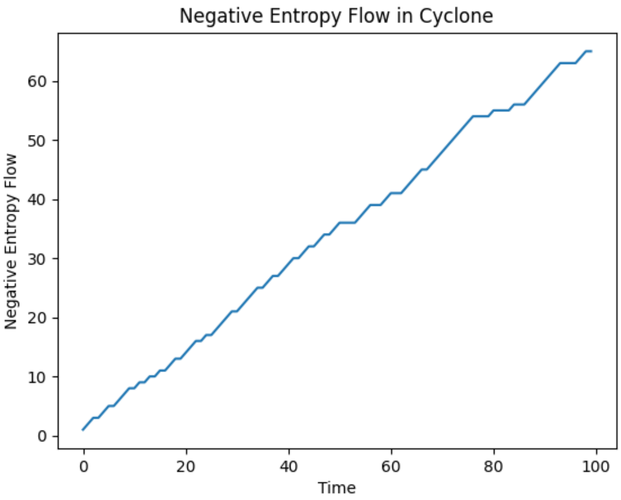


Fig 7. Negative Entropy Flow in Biporjoy

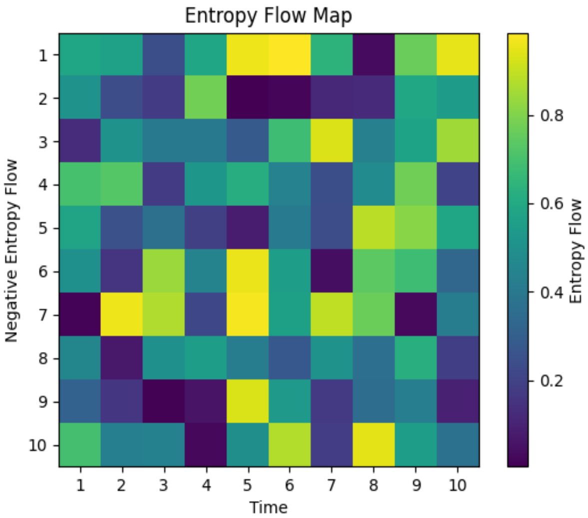


Fig 8. Entropy Flow Distribution in Biporjoy

Result:

In this section, we will compare the results from both the classical negentropy and the one computed from quantum annealing. For cyclone "Mocha" we got, Negative Entropy: -3151.5715669675296 from the first part and from the second part we got Negative Entropy Flow: - 3164, which is quite closer to one another and the graphs from both the parts of negative entropy flow is also quite similar.

For cyclone "Biporjoy" we got Negative Entropy: -3443.15854156927 from the first part and from the second part we got Negative Entropy Flow: - 3412 and the values are almost similar likewise the graphs of negative entropy flow in both the cases are also same. Here we got the conclusion that quantum simulated annealing gives more accurate and closer value to the actual one and it even shows the small amount of fluctuations in entropy flow on the graphs and gives the details of negative entropy in each quantum states of the system.

Conclusion:

In conclusion, this project aimed to explore various aspects of cyclones, including their formation, dynamics, and thermodynamic properties. By studying the concepts of entropy and negative entropy, we gained insights into the organization and complexity of cyclonic systems. Through the use of scientific literature and mathematical models, we examined the relationship between entropy and cyclone strength, recognizing that it is a complex and multifaceted phenomenon. While stronger cyclones may exhibit certain characteristics associated with higher order or organization, it is important to consider a range of factors and environmental conditions when analysing cyclone behaviour. Overall, this project contributes to our understanding of cyclones and highlights the intricate interplay between thermodynamics, meteorology, and atmospheric dynamics in these powerful weather systems.

Acknowledgement:

I would like to express our sincere gratitude to professor Kalipada Adhikari whose work has contributed to my understanding of cyclones and thermodynamics. His contributions has been instrumental in shaping my knowledge of quantum information theory and providing the foundation for this project.

Conflict of interest:

There is no conflict of interest to declare regarding this project.

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