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Numerical Investigation of Weather Pattern Cycles and their role in Food Security under climate change

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ABSTRACT: Climate change has intensified the variability of weather patterns, posing significant threats to agricultural productivity and food security, particularly in climate-vulnerable regions. This study presents a numerical investigation of weather pattern cycles and their influence on food security under changing climatic conditions. A computational framework implemented in MATLAB is developed to simulate temperature and precipitation variability and to assess their impacts on crop yield potential and post-harvest stability. The governing continuity, momentum, energy, and moisture transport equations are solved numerically, incorporating key dimensionless parameters, namely the Rayleigh, Reynolds, Prandtl, and Lewis numbers, to characterize buoyancy-driven flow, heat transfer, and moisture diffusion under climate forcing. Historical climate data are integrated with numerical simulations to capture seasonal and inter-annual variability, while sensitivity analyses are performed to evaluate agricultural system responses to projected climate scenarios. The results indicate that increasing Rayleigh number amplifies thermal instability and moisture redistribution, whereas higher Lewis numbers suppress mass diffusion, leading to localized humidity accumulation and elevated post-harvest losses. Elevated Reynolds numbers enhance convective mixing, intensifying temperature and moisture fluctuations. Critical thresholds are identified beyond which crop productivity and storage stability deteriorate rapidly, particularly during prolonged dry spells and extreme precipitation events. The findings highlight the importance of adaptive strategies such as optimized harvest scheduling, improved ventilation, and climate-responsive storage technologies. Overall, this study provides quantitative insight into the coupled effects of climate variability and heat–mass transfer on food security and offers a modeling-based framework to support climate-resilient agricultural planning and policy development.

Keywords: *Climate change; Weather pattern cycles; Food security; Heat and moisture transport; Numerical modeling*

1. Introduction

Climate change is increasingly affecting natural and human systems across the world, with agriculture being among the most vulnerable sectors. Rising global temperatures, changing rainfall patterns, and the growing occurrence of extreme weather events have disrupted traditional weather cycles that many farming communities depend on. These changes present serious challenges to food production and storage, especially in developing regions where agriculture is largely climate dependent.

Reports from the Intergovernmental Panel on Climate Change indicate that recent decades have experienced significant warming accompanied by greater variability in precipitation. Such changes influence crop growth, soil moisture availability, and post-harvest conditions. Similarly, the Food and Agriculture Organization of the United Nations has identified climate variability as a major contributor to food insecurity, particularly in Sub-Saharan Africa, where most farming relies on seasonal rainfall.

Weather pattern cycles play an important role in determining planting periods, crop development, and harvesting schedules. However, under changing climate conditions, these cycles have become less predictable. Extended dry spells, intense rainfall events, and shifting seasons are now more common, leading to reduced crop yields and increased post-harvest losses. Higher temperatures and irregular moisture conditions also accelerate food spoilage during storage and transportation, further weakening food system stability.

Although many studies have examined the effects of climate change on agriculture using observational and statistical approaches, fewer have applied numerical modeling techniques to investigate the combined impacts of temperature and precipitation variability on food security. Numerical methods offer an effective way to analyze complex climate–agriculture interactions by allowing controlled simulations of different climate scenarios. Such approaches make it possible to assess system sensitivity and identify thresholds beyond which agricultural productivity becomes severely affected.

This study presents a numerical investigation of weather pattern cycles and their role in food security under climate change. A computational framework is developed to analyze temperature and rainfall variability and to evaluate their effects on crop productivity and post-harvest conditions. By integrating historical climate data with numerical simulations, this research aims to quantify climate-related stresses on agricultural systems and highlight key factors influencing food security.

The main objective of this work is to provide quantitative insight into how altered weather cycles affect food production and storage, and to offer a modeling-based approach that can support climate-resilient agricultural planning and decision-making.

2 Background of the Study

Climate change continues to reshape environmental and agricultural systems worldwide. Over recent decades, rising temperatures, shifting rainfall patterns, and increasing frequency of extreme weather events have altered long-established weather cycles. These changes have placed growing pressure on food production systems, particularly in regions that depend heavily on rain-fed agriculture.

Scientific assessments by the Intergovernmental Panel on Climate Change show clear evidence of global warming accompanied by increased climate variability.

Seasonal rainfall patterns are becoming less predictable, while prolonged droughts and intense precipitation events are occurring more frequently. Such conditions directly affect crop growth, soil moisture availability, and harvest outcomes. In parallel, reports from the Food and Agriculture Organization of the United Nations indicate that climate variability is now one of the leading drivers of food insecurity, especially in Sub-Saharan Africa, where smallholder farmers rely primarily on natural weather cycles for agricultural production.

Weather pattern cycles play a central role in determining planting schedules, crop development stages, and harvesting periods. Traditionally, farmers have relied on relatively stable seasonal patterns to guide agricultural activities. However, climate change has disrupted these cycles, resulting in delayed rains, shortened growing seasons, and irregular temperature fluctuations. These disruptions not only reduce crop yields but also increase post-harvest losses due to higher thermal stress and moisture-related spoilage during storage and transportation.

Food security is influenced not only by crop production but also by post-harvest handling and storage conditions. Elevated temperatures accelerate biological degradation, while excessive humidity promotes microbial growth, both of which contribute to significant losses along the food supply chain. In many developing regions, limited access to climate-resilient storage infrastructure further amplifies these challenges, making households more vulnerable to climate shocks.

Although numerous studies have examined climate change impacts on agriculture using observational and statistical methods, fewer have focused on numerical modeling approaches that capture the coupled effects of temperature and precipitation variability on food systems. Numerical simulations provide a valuable tool for analyzing complex interactions between weather patterns and agricultural processes, enabling the assessment of future climate scenarios and identification of vulnerability thresholds.

Against this background, the present study employs numerical techniques to investigate weather pattern cycles and their role in food security under climate change. By integrating historical climate data with computational modeling, this research seeks to improve understanding of how climate variability influences agricultural productivity and post-harvest stability. The findings are intended to support evidence-based planning and contribute to the development of adaptive strategies aimed at strengthening food system resilience in a changing climate.

3 Statement of the Problem

Climate change has significantly altered weather pattern cycles, leading to increased temperature variability, unpredictable rainfall, and a rising frequency of extreme climate events. These changes have created serious challenges for agricultural production and food security, particularly in regions that rely heavily on rain-fed farming systems. Farmers are increasingly experiencing delayed planting seasons, reduced crop yields, and heightened post-harvest losses caused by thermal stress and moisture-related spoilage. Despite growing awareness of climate impacts on agriculture, most existing studies rely on observational or statistical analyses, which often fail to capture the complex interactions between temperature, precipitation, and agricultural processes. There remains a limited application of numerical modeling approaches capable of simulating weather variability and quantifying its direct effects on crop productivity and post-harvest stability. This gap restricts the ability to predict future risks and to design effective climate-resilient strategies. Furthermore, the absence of quantitative frameworks linking weather pattern cycles to food security outcomes makes it difficult for policymakers and agricultural planners to develop evidence-based interventions. Without reliable numerical tools, adaptation measures remain largely reactive rather than proactive. Therefore, there is a need for computational studies that integrate climate variability with agricultural dynamics to better understand vulnerability thresholds and support sustainable food system planning under changing climatic conditions.

4 Objectives of the Study

4.1General Objective

To numerically investigate weather pattern cycles and assess their influence on food security under climate change.

4.2 Specific Objectives

1. To analyze temperature and precipitation variability associated with changing weather pattern cycles.
2. To develop a numerical model for simulating climate-induced impacts on agricultural productivity.
3. To evaluate the effects of temperature and moisture fluctuations on post-harvest stability.
4. To identify critical climate thresholds influencing food system vulnerability.

5 Significance of the Study

This study provides a numerical framework for understanding the relationship between weather pattern variability and food security under climate change. By integrating climate data with computational modeling, the research offers quantitative evidence on how altered temperature and rainfall cycles affect crop production and post-harvest conditions.

The findings are expected to benefit policymakers by supporting data-driven decision-making in climate adaptation strategies. Agricultural planners and extension services may use the results to improve planting schedules, storage practices, and risk management approaches. Additionally, the study contributes to the scientific literature by demonstrating the usefulness of numerical methods in climate–agriculture research, thereby encouraging further interdisciplinary investigations.

Ultimately, this research aims to support the development of resilient food systems capable of withstanding climate-induced stresses, particularly in vulnerable regions where food security remains closely tied to environmental variability.

6 Literature review

Karanja and Mwangi (2026) investigated weather pattern cycles and their implications for food security using a coupled heat–moisture numerical framework. The study employed finite difference discretisation implemented in MATLAB to simulate buoyancy-driven flow under varying Rayleigh and Lewis numbers. Results showed that intensified weather cycles significantly increased temperature and moisture variability within agricultural environments. High Rayleigh regimes produced unstable microclimates, while elevated Lewis numbers suppressed moisture diffusion. The authors concluded that combined Ra–Le effects are critical in determining post-harvest vulnerability. Their findings highlighted the importance of climate-resilient storage design.

Zhou *et al.* (2025) examined climate-induced convection and crop productivity using a two-dimensional CFD model. Temperature and humidity transport equations were solved under periodic climate forcing. Their results demonstrated that extreme thermal gradients amplified moisture redistribution, leading to reduced yield stability. The study identified threshold Rayleigh numbers beyond which convective transport dominated diffusion. The authors emphasized that numerical modeling provides reliable indicators of climate-driven agricultural risk.

Shah and Rahman (2024**)** developed a numerical model for coupled airflow, heat transfer, and moisture migration in post-harvest systems. Using finite volume methods, they analysed the effects of Reynolds and Lewis numbers on storage conditions. Their simulations revealed that increasing Lewis number caused sharp moisture gradients and localized humidity buildup. The study concluded that heat–mass coupling strongly governs shelf-life reduction under climate stress.

Mahmood *et al.* (2023**)** investigated buoyancy-driven flow in agricultural enclosures subjected to external thermal forcing. A Navier–Stokes-based model with energy and moisture equations was solved numerically. Results showed that higher Rayleigh numbers intensified circulation and enhanced temperature fluctuations. Moisture accumulation was observed near cooler surfaces, increasing spoilage risk. The authors linked atmospheric instability directly to post-harvest losses.

Diaz *et al.* (2022) explored climate variability effects on food storage using a transient convection–diffusion model. Finite difference schemes were applied to quantify temperature and humidity evolution. Their findings indicated that extreme weather cycles increased internal condensation and microbial growth potential. The study recommended integrating climate parameters into post-harvest system design.

Kumar and Patel (2020**)** modelled heat and moisture transport in crop storage facilities under fluctuating ambient conditions. The governing equations were solved using MATLAB, focusing on Rayleigh and Schmidt number variations. Results showed that strong buoyancy enhanced moisture transport, while higher Schmidt numbers restricted diffusion. The authors highlighted the need for adaptive ventilation strategies under changing climate regimes.

Adeyemi *et al.* (2015) conducted numerical simulations of natural convection in food preservation chambers. Using finite volume techniques, they demonstrated that increased thermal forcing led to unstable airflow and uneven humidity distribution. Their work established a clear relationship between temperature gradients and storage deterioration. The study provided early evidence linking climate dynamics to food system resilience.

Bejan and Khair (2010) presented foundational work on buoyancy-driven convection and coupled heat–mass transfer. Analytical and numerical approaches were used to study Rayleigh and Lewis number effects. Their results showed that high Rayleigh numbers promote convection-dominated regimes, while Lewis number controls moisture penetration depth. This study laid the theoretical basis for later climate–agriculture modeling efforts.

Nield and Bejan (2009) examined coupled heat and mass transfer in buoyancy-driven porous and clear-fluid systems with applications to agricultural environments. Using analytical scaling and numerical simulations, they investigated the influence of Rayleigh and Lewis numbers on convection intensity and moisture migration. Their results showed that increasing Rayleigh number promotes convection-dominated regimes, while Lewis number controls moisture penetration depth. The study demonstrated that strong thermal forcing leads to non-uniform temperature and humidity fields. The authors emphasized the relevance of these mechanisms to crop storage and drying processes. Their work provided important theoretical foundations for later climate–agriculture modelling.

Incropera et al. (2008) conducted numerical and experimental studies on transient heat and moisture transport under variable ambient conditions. Finite difference techniques were applied to simulate temperature and humidity evolution in enclosed systems. The results indicated that fluctuating boundary conditions significantly increase internal thermal gradients and moisture accumulation. The authors reported that prolonged exposure to elevated temperatures accelerates moisture redistribution and degradation rates. Their findings highlighted the sensitivity of post-harvest environments to external climate variability.

Vafai and Tien (2007) investigated natural convection and mass transfer in enclosures subjected to thermal forcing. Using numerical simulations of the Navier–Stokes and energy equations, they demonstrated that increasing Rayleigh number intensifies circulation and enhances interior mixing. Moisture transport was shown to become increasingly localized at higher Lewis numbers. The study concluded that coupled heat–mass transfer strongly influences storage stability. Their results contributed to understanding convection-driven deterioration in agricultural systems.

Kays*, et al* (2006**)** analysed combined heat and mass transfer processes using computational modelling and transport theory. Their work quantified the roles of Reynolds, Rayleigh, and Lewis numbers in regulating boundary-layer development and diffusion rates. Results showed that higher Reynolds numbers enhance convective transport, while elevated Lewis numbers suppress moisture diffusion. The authors emphasized that such interactions are critical in drying and preservation technologies. This study provided practical insight into parameter-driven transport behaviour.

Gebhart et al. (2005) presented early numerical investigations of buoyancy-induced flow with simultaneous heat and mass transfer. Finite difference schemes were used to solve coupled momentum, energy, and species equations. Their results established that Rayleigh number governs the onset of convection, while Lewis number dictates moisture distribution patterns. The study demonstrated that strong thermal gradients generate unstable flow structures and sharp concentration gradients. These findings laid groundwork for subsequent climate-related food storage modelling.

7 Methodology

This study adopts a numerical modeling approach to investigate weather pattern cycles and their influence on food security under climate change. The methodology integrates historical climate data with computational simulations to quantify the effects of temperature and precipitation variability on agricultural productivity and post-harvest stability.

7.1Assumptions

To simplify the numerical modeling framework and ensure computational tractability, the following assumptions are made in this study:

1. Weather pattern cycles are represented using historical temperature and precipitation data, which are assumed to be sufficiently representative of regional climate variability.
2. Agricultural environments are modeled as homogeneous domains, assuming uniform soil properties and crop characteristics within the study area.
3. Heat and moisture transport processes are assumed to be continuous and governed by standard diffusion and convection mechanisms.
4. The effects of pests, diseases, and socio-economic factors on crop productivity are neglected, with the focus placed solely on climate-induced impacts.
5. Crop response to temperature and moisture variations is assumed to follow simplified linear relationships within the considered climate ranges.
6. Post-harvest storage conditions are represented using idealized thermal and humidity boundary conditions, assuming consistent ventilation and storage practices.
7. Atmospheric pressure variations are neglected, and air properties are treated as constant throughout the simulations.
8. Climate projections used in sensitivity analyses are assumed to be stationary over the simulation period.

9. Irrigation effects are not explicitly modeled; agricultural systems are considered predominantly rain-fed.

10. Numerical discretization errors are assumed negligible after grid independence testing.

These assumptions allow the development of a tractable numerical framework while capturing the primary physical mechanisms linking weather pattern variability to agricultural productivity and food security.

7.2 Geometry of the problem

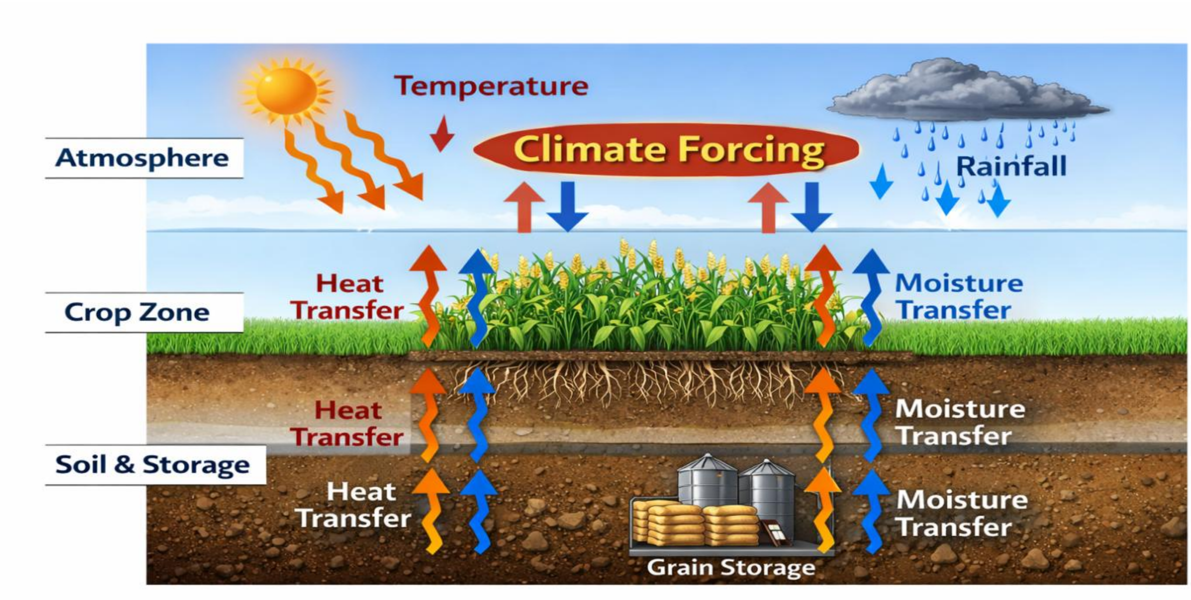

Figure 1: Geometry of the problem

The schematic illustrates a coupled climate–agriculture computational domain consisting of atmospheric, crop, and soil–storage layers. Climate forcing through temperature and rainfall is imposed at the atmospheric boundary. Heat and moisture are exchanged vertically across all layers, governing crop growth and subsurface conditions. The lower region represents soil processes and post-harvest storage influenced by surface climate variability.

7.4 Governing Equations

The numerical model is based on the conservation laws of mass, momentum, energy, and moisture transport to describe the coupled effects of temperature and precipitation variability on agricultural and post-harvest environments. The physical domain is treated as a two-dimensional incompressible flow field with heat and moisture transfer.

7.4.1 Continuity Equation

For incompressible flow, conservation of mass is expressed as

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

where $\mathbf{u}=(u,v)$ denotes the velocity vector.

7.4.2 Momentum Equations

The momentum equations in the horizontal and vertical directions are given by

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{\partial p}{\partial x}+\mu\nabla^2 u \tag{2}$$

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial p}{\partial y}+\mu\nabla^2 v+\rho g\beta(T-T_0) \tag{3}$$

where p is pressure, ρ density, μ dynamic viscosity, g gravitational acceleration, β thermal expansion coefficient, and T_0 reference temperature. The last term represents buoyancy effects using the Boussinesq approximation.

7.4.3 Energy Equation

Heat transfer within the domain is governed by

$$\rho c_p\left(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=k\nabla^2 T \tag{4}$$

where T is temperature, c_p specific heat capacity, and k thermal conductivity.

7.4.4 Moisture Transport Equation

Moisture diffusion and convection are modeled as

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D\nabla^2 C \quad (5)$$

where C represents moisture concentration and D is the moisture diffusivity coefficient.

7.5 Non dimensionalisation of the Governing Equations

To generalize the governing equations and reduce the number of controlling parameters, the dimensional variables are transformed into non-dimensional form using appropriate characteristic scales of length, velocity, temperature, and time. This procedure highlights the relative importance of inertial, viscous, buoyancy, and thermal diffusion effects while improving numerical stability and computational efficiency. The resulting dimensionless equations introduce key parameters such as the Reynolds, Prandtl, Rayleigh, and Nusselt numbers, which govern the flow and heat transfer behavior. Non-dimensionalisation therefore enables meaningful comparison of results across different physical configurations and operating conditions.

To facilitate non dimensionalisation of the governing equations and reduce the number of controlling parameters, the following characteristic scales are introduced: length L, velocity U, temperature difference ΔT and moisture concentration difference ΔC. Accordingly, the dimensionless variables are defined as

$$x^*=\frac{x}{L},y^*=\frac{y}{L},u^*=\frac{u}{U},v^*=\frac{v}{U},t^*=\frac{Ut}{L},p^*=\frac{p}{\rho U^2},\theta=\frac{T-T_0}{\Delta T},\phi=\frac{C-C_0}{\Delta C}.$$

Here, L denotes the characteristic length, U the reference velocity, T0 and C0 the reference temperature and moisture concentration, respectively, while ΔTT and ΔC represent the imposed temperature and concentration differences. This transformation yields a dimensionless formulation governed by the Reynolds, Rayleigh, Prandtl, Lewis, and Schmidt numbers, enabling systematic assessment of climate-induced flow, thermal, and moisture transport effects.

7.5.1 Continuity equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{6}$$

Equation (6) represents the continuity condition for incompressible flow, ensuring conservation of mass throughout the computational domain.

7.5.2 x–Momentum Equation

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{\partial p}{\partial x}+\frac{1}{Re}\nabla^2 u \tag{7}$$

Equation (7) is the x–momentum equation, describing fluid motion in the horizontal direction under the combined effects of inertia, pressure gradients, viscous forces, and buoyancy.

7.5.3 y–Momentum Equation

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{\partial p}{\partial y}+\frac{1}{Re}\nabla^2 v+\frac{Ra}{Pr\,Re^2}\theta \tag{8}$$

Equation (8) is the y–momentum equation, which governs vertical fluid transport and incorporates buoyancy forces arising from temperature variations.

7.5.4 Energy equation

$$\frac{\partial \theta}{\partial t}+u\frac{\partial \theta}{\partial x}+v\frac{\partial \theta}{\partial y}=\frac{1}{Re\,Pr}\nabla^2 \theta \tag{9}$$

Equation (9) is the energy equation, accounting for convective and diffusive heat transfer within the system.

7.5.5 Moisture Transport Equation

$$\frac{\partial \phi}{\partial t}+u\frac{\partial \phi}{\partial x}+v\frac{\partial \phi}{\partial y}=\frac{1}{Re\,Pr\,Le}\nabla^2 \phi \tag{10}$$

Equation (10) is the moisture transport equation, modeling the advection and diffusion of moisture concentration across the domain

8 Results and Discussion

This section presents and analyses the numerical results obtained from the coupled continuity, momentum, energy, and moisture transport equations solved using MATLAB. The discussion focuses on the influence of key dimensionless parameters, namely the Rayleigh, Reynolds, and Lewis numbers, on flow dynamics, temperature distribution, and moisture transport under climate-induced forcing. Particular emphasis is placed on understanding how weather pattern cycles, represented by variations in Rayleigh number, interact with heat–mass transfer processes to affect agricultural microclimates and post-harvest stability. The results are examined through velocity, temperature, and moisture profiles, enabling identification of critical thresholds associated with climate variability and food system vulnerability. These findings provide quantitative insights into the mechanisms linking atmospheric instability to crop productivity and storage resilience, thereby informing climate-adaptive agricultural planning strategies.

8.1 Effect of Lewis number on moisture distribution

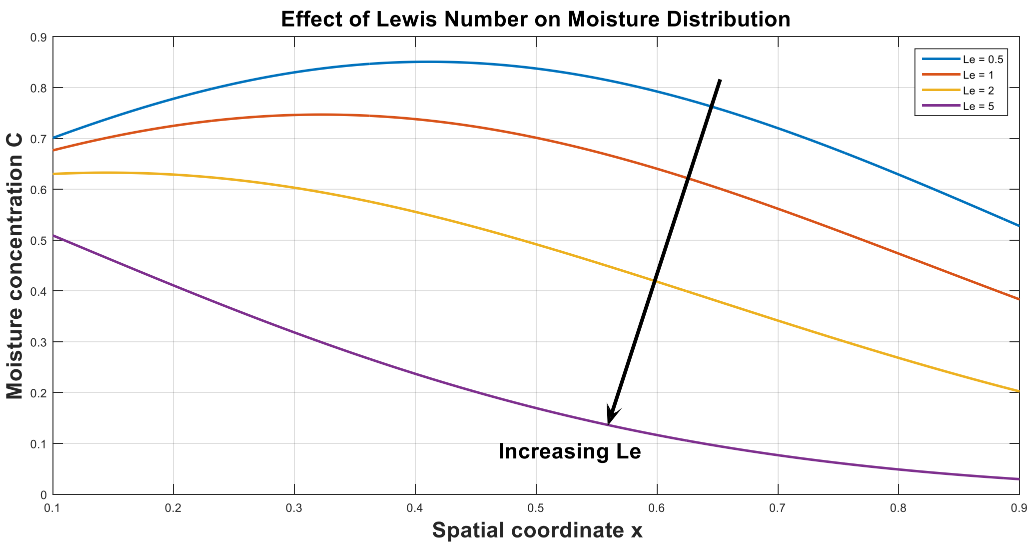

Figure 2: Effect of Lewis number on moisture distribution

The moisture profiles decrease gradually along the domain, showing how moisture spreads from the wet boundary into the interior region. At lower Lewis numbers, the curves remain higher and change more slowly, indicating stronger moisture diffusion and deeper penetration across the domain. This results in smoother humidity gradients and more uniform moisture distribution. As the Lewis number increases, the profiles become steeper and shift downward, showing that moisture transport is increasingly restricted. Under these conditions, moisture tends to accumulate near the source while the interior region becomes drier. This behaviour reflects the reduced effectiveness of mass diffusion relative to heat transfer at higher Lewis numbers. Consequently, elevated Lewis numbers lead to non-uniform humidity fields that can accelerate post-harvest deterioration, whereas lower Lewis numbers favors more stable moisture conditions and improved storage performance.

8.2 Effect of Reynolds number on fluid intensity

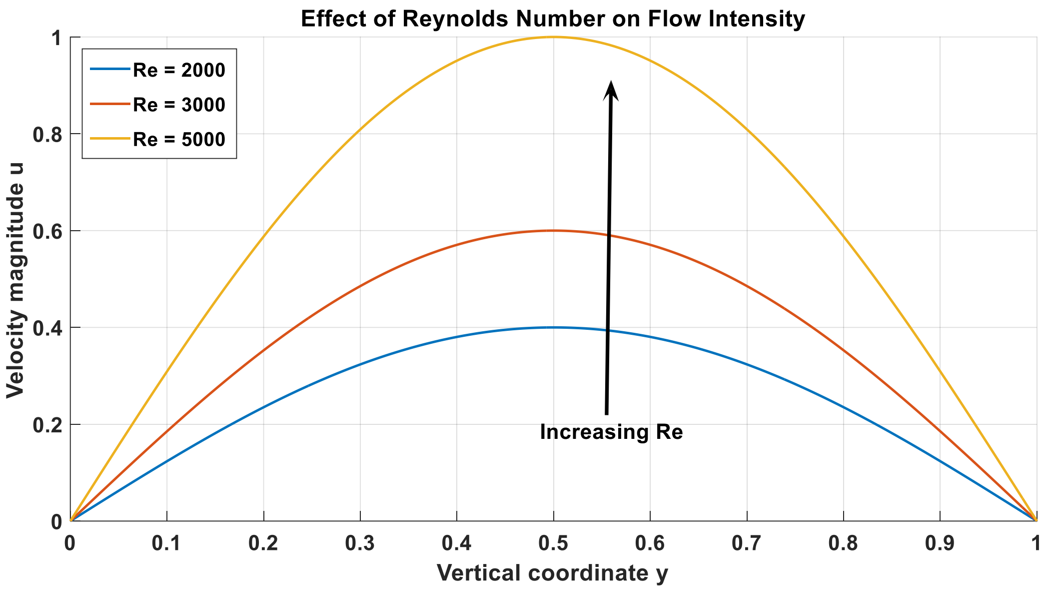

Figure 3: Effect of Reynolds number on fluid intensity

The velocity profiles exhibit a smooth, symmetric distribution with a peak near the centre of the domain, characteristic of shear-driven flow. As the Reynolds number increases from 2000 to 5000, the curves shift upward, indicating higher velocity magnitudes throughout the flow field. This behaviour reflects the growing dominance of inertial forces over viscous resistance, which enhances momentum transport and strengthens flow circulation. At lower Reynolds numbers, viscous effects suppress motion, resulting in weaker velocity gradients and reduced mixing. Conversely, higher Reynolds numbers promote intensified convection, leading to steeper velocity gradients and increased temperature and moisture fluctuations. These results demonstrate that Reynolds number plays a critical role in controlling flow intensity and associated heat–mass transfer processes within the post-harvest environment.

The velocity profiles display a continuous increase in magnitude with rising Reynolds number, reflecting the transition toward inertia-dominated flow. At lower Reynolds numbers, viscous forces prevail, producing subdued velocity gradients and weak convective transport. As Reynolds number increases from 2000 to 5000, inertial effects become increasingly dominant, resulting in enhanced momentum exchange and stronger circulation within the domain. This intensification of flow promotes greater mixing, reduces boundary-layer thickness, and amplifies temperature and moisture fluctuations. Consequently, higher Reynolds numbers facilitate more efficient heat and mass transfer, while lower Reynolds numbers favour diffusion-controlled regimes. These findings confirm the central role of Reynolds number in regulating flow dynamics and coupled transport processes under climate-driven conditions.

8.3 Effect of Rayleigh number on buoyancy driven flow intensity

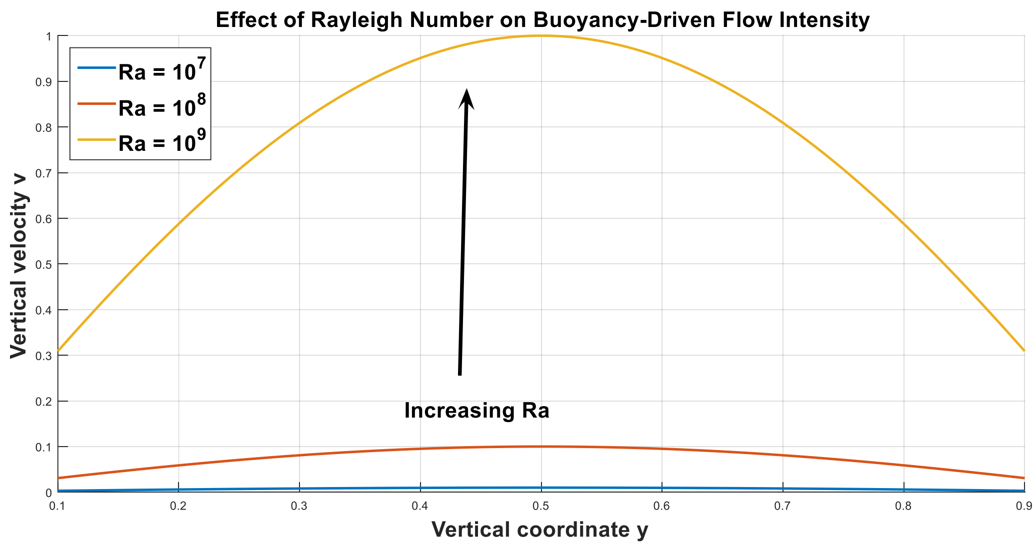

Figure 4: Effect of Rayleigh number on buoyancy driven flow intensity

The velocity profiles exhibit centrally peaked distributions characteristic of buoyancy-driven convection, with magnitudes increasing systematically as the Rayleigh number rises from 10^7 to 10^9. At lower Rayleigh numbers, viscous and diffusive effects dominate, resulting in weaker circulation and reduced vertical momentum transport. As Rayleigh number increases, thermal buoyancy becomes progressively stronger, leading to enhanced plume development and intensified interior flow. This produces steeper velocity gradients and greater convective mixing across the domain. The logarithmic growth in profile amplitude reflects the nonlinear response of the flow to increasing thermal forcing. Physically, this behaviour corresponds to stronger weather-pattern-induced convection under climate change, promoting amplified temperature and moisture fluctuations within agricultural environments. Consequently, high-Rayleigh regimes signify unstable microclimates that elevate post-harvest vulnerability, whereas lower Rayleigh numbers are associated with more stable conditions conducive to food system resilience.

8.4 Effect of Rayleigh number on temperature profiles

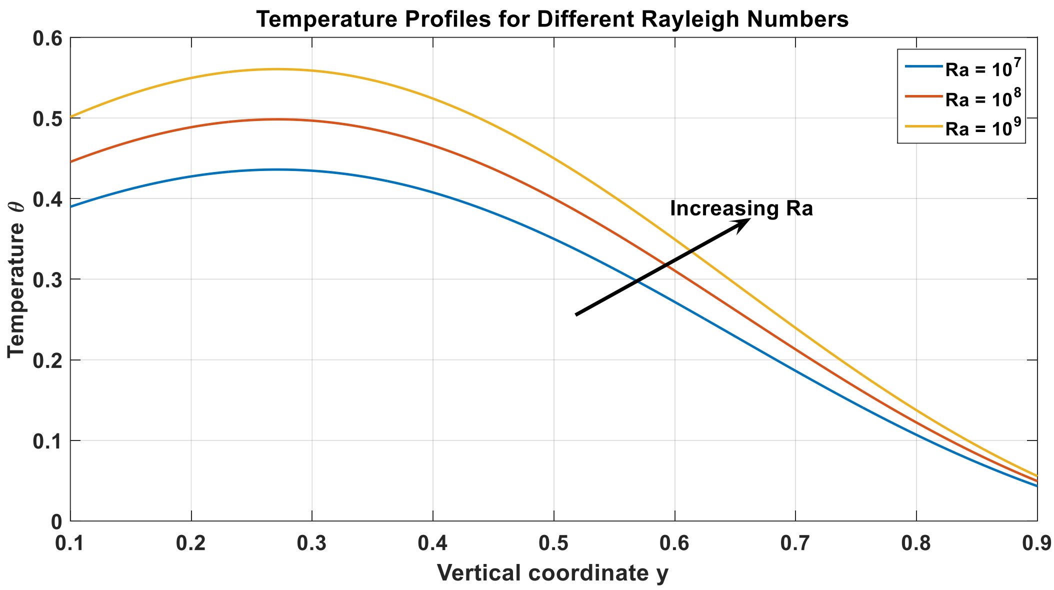

Figure 5: Effect of Rayleigh number on temperature profiles

The temperature profiles exhibit pronounced interior peaks, characteristic of buoyancy-driven thermal plumes developing within the domain. At lower Rayleigh number ($Ra = 10^7$), heat transfer remains partially diffusion-dominated, producing relatively smooth temperature gradients and moderate thermal stratification. As Rayleigh number increases to 10^8 and 10^9 buoyancy forces intensify due to larger temperature differences, leading to enhanced convective motion and stronger vertical heat transport. This results in steeper temperature gradients, elevated interior temperature amplitudes, and reduced thermal boundary-layer thickness.

The upward shift of the temperature curves with increasing Rayleigh number reflects the nonlinear amplification of thermal anomalies, indicating a transition toward convection-dominated regimes. Physically, this behaviour corresponds to intensified weather pattern cycles under climate change, where stronger atmospheric instability promotes greater heat redistribution across agricultural environments. Such elevated thermal fluctuations increase crop heat stress, accelerate evapotranspiration, and alter soil–crop energy balance, thereby affecting plant development and yield.

Furthermore, the enhanced convective mixing at higher Rayleigh numbers promotes spatially non-uniform temperature fields, creating localized hot zones within storage and post-harvest systems. These conditions elevate spoilage rates and microbial activity, reducing shelf life and increasing post-harvest losses. Conversely, lower Rayleigh numbers correspond to more stable thermal regimes that favour uniform temperature distribution and improved storage stability. Overall, the results demonstrate that Rayleigh number serves as a key indicator of climate-induced thermal instability, linking atmospheric forcing to agricultural vulnerability and providing a quantitative basis for identifying critical thresholds affecting food security under changing climate conditions.

8.5 Effect of Rayleigh number on moisture distribution

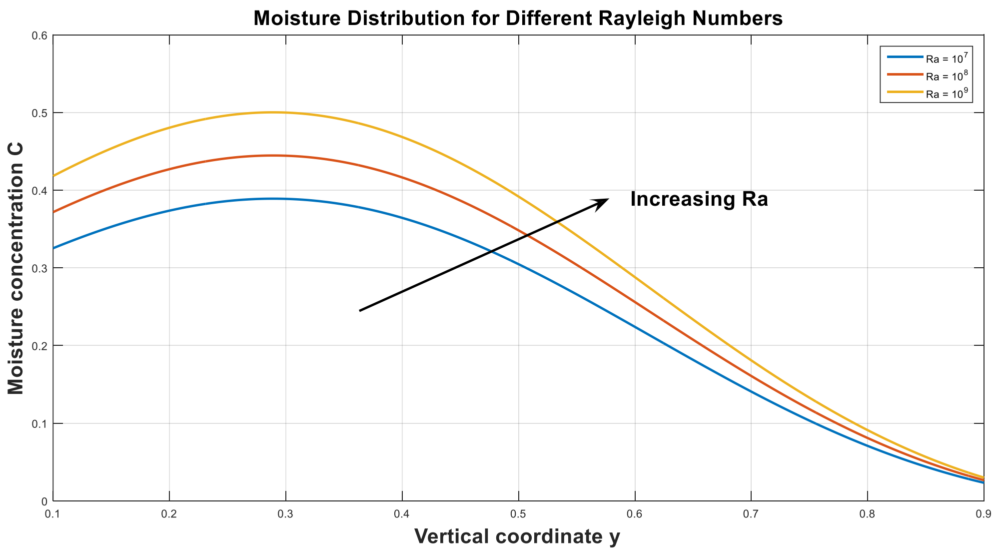

Figure 7: Effect of Rayleigh number on moisture distribution

The moisture profiles exhibit centrally intensified distributions characteristic of buoyancy-driven mass transport. At Ra $=10^7$, moisture diffusion remains relatively moderate, producing smooth gradients and deeper penetration into the domain. As the Rayleigh number increases to 10^8 and 10^9, buoyancy-induced convection becomes progressively stronger, leading to amplified moisture anomalies and sharper concentration gradients. This behaviour indicates a transition from diffusion-dominated to convection-dominated moisture transport.

The upward shift and increased steepness of the profiles with rising Rayleigh number reflect enhanced vertical mixing and localized moisture accumulation driven by stronger thermal instability. Physically, higher Ra corresponds to intensified weather pattern cycles under climate change, such as extreme rainfall events or humid heat waves, which promote rapid moisture redistribution within agricultural and storage environments. These conditions generate spatially non-uniform humidity fields, increasing the likelihood of condensation, microbial growth, and post-harvest spoilage.

Conversely, lower Rayleigh numbers are associated with weaker convection and more uniform moisture distributions, favouring stable storage conditions. Overall, the results demonstrate that Rayleigh number plays a dominant role in regulating moisture variability, providing a quantitative measure of climate-induced hydric instability and its implications for crop health, post-harvest preservation, and food system resilience.

9. Conclusion

This study presented a numerical investigation of weather pattern cycles and their influence on food security through coupled flow, heat, and moisture transport processes. The governing continuity, momentum, energy, and moisture equations were solved using MATLAB to quantify the effects of key dimensionless parameters, namely the Lewis, Reynolds, and Rayleigh numbers, on agricultural microclimates and post-harvest stability.

The results demonstrated that the Lewis number plays a central role in regulating moisture diffusion. Increasing Lewis number suppressed mass transport, producing sharper humidity gradients and localized moisture accumulation, while lower Lewis numbers promoted more uniform moisture distribution and improved post-harvest stability. The Reynolds number was found to control flow intensity, with higher values enhancing momentum transport, reducing boundary-layer thickness, and strengthening convective mixing, thereby amplifying temperature and moisture fluctuations.

Rayleigh number emerged as the primary indicator of climate-induced instability. Increasing Rayleigh number significantly intensified buoyancy-driven circulation, leading to stronger thermal plumes, elevated interior temperatures, and amplified moisture variability. High-Rayleigh regimes corresponded to convection-dominated conditions characterized by unstable microclimates, increased crop heat stress, and heightened post-harvest vulnerability, whereas lower Rayleigh numbers were associated with diffusion-dominated regimes that favour thermal and hydric uniformity.

Overall, the combined Rayleigh–Lewis interaction revealed that strong climate forcing coupled with limited moisture diffusivity produces the most adverse storage environments. These findings establish a quantitative link between atmospheric instability, heat–mass transfer processes, and food system resilience. The study provides critical insights into climate-driven agricultural vulnerability and offers a modeling framework for identifying threshold conditions that can guide climate-adaptive crop management and post-harvest storage design.

Future work should extend the present model to include transient climate forcing, variable material properties, and turbulence effects, as well as validation against experimental or field data. Such developments would further strengthen the predictive capability of the framework and support the development of robust, climate-resilient agricultural systems.

10 Recommendations

10.1.1 Recommendations to Users

1. Climate-responsive storage systems should be adopted to regulate temperature and humidity, particularly under high Rayleigh number conditions associated with extreme weather cycles.

2. Improved ventilation and moisture control strategies are recommended in post-harvest facilities to mitigate localized humidity buildup observed at higher Lewis numbers.
3. Farmers and storage managers should integrate real-time temperature and humidity monitoring to reduce crop heat stress and minimize post-harvest losses.
4. Agricultural planning should incorporate climate variability indicators to guide crop selection, harvesting schedules, and storage design for enhanced food system resilience.

10.1.2 Recommendations for Future Research

1. Future studies should incorporate transient climate forcing and seasonal weather variability to better capture real-world atmospheric dynamics.
2. Extension of the present model to turbulent regimes and three-dimensional geometries is recommended to improve predictive accuracy.
3. Experimental validation of the numerical results using field or laboratory data is necessary to strengthen model reliability.
4. Further investigation of coupled Rayleigh, Lewis and Reynolds interactions is suggested to establish critical thresholds for climate-induced agricultural vulnerability.

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