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Probabilistic Evaluation of Climate Models for Seasonal Forecasting in the MENA Region

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TABLE DES MATIÈRES

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PREFACE

The MENA seasonal forecasting models have undergone both probabilistic and deterministic evaluations. This research study is regarded as the pioneering work and the first of its kind in this area which helps in situational context improvement in seasonal forecasting models. Given the alarming rate of increase in the impacts caused by extreme climatic events including severe droughts, and extreme heat and other climate sensitive issues in the MENA region, this work is a key contribution towards alleviating these issues=

Due to climatic extremes in the MENA region, agriculture, human livelihood, and natural resources are heavily affected. Consequently, it has become almost necessary to have forecasts of seasons that are credible so as to characterize the impacts, or to enhance preparedness. Although seasonal forecasting models have been widely researched and practiced in many parts of the world, their use in MENA countries' local level remains scarce. This gap is resolved in this study, providing new knowledge and tools for climate scientists working in the region.

In this work, we intend to broaden the knowledge fabric of climate change science by focusing on the climate change and variability vulnerability of the MENA region. The results obtained not only improve the comprehension of the dynamics of the local climate, but also lays a framework for specific approach to be employed for adaptation strategies.

We are immensely grateful to every individual or organization who has helped support this project and guided us through uncharted territory in the spectrum of MENA climate predictions.

CHAPITRE 1

OVERVIEW AND RATIONALE OF THE STUDY

The last couple of decades have witnessed a surge in demand for seasonal climate forecasting. Global advancements in space science and technology have lead to the better anticipation of climate seasons up to a thorugh range of 3-12 months. This is crucial for effective planning in major industries like agriculture or energy management, amongst others. These advancements breed an increased dependence on seasonal forecasting and in turn create a higher demand for accurate forecasting mechanisms. Therefore two central methodologies have witnessed prominence – deterministic and probabilistic methods. A hindsight understanding of these mechanisms is imperative, as they are useful for evaluating and understanding the shortcomings and effectiveness of different models employed in forecasting seasonal amps.

Probabilistic forecasts take one step forward, do not try to predict an ideal scenario and present different potential outcomes, each with a defined probability. Efforts, though different, instruct towards the same ends ; meeting a specific operational/strategic need. Lorenz's butterfly effect presents the case for one such endeavor- it shows how a non-linear system's response can drastically alter depending on the initial conditions. Such chaos is especially present in weather and climate systems where even the slightest details can have large ramifications over longer periods.

The study on the other hand tries to develop such relationships that integrate conceptual developments in seasonal forecasting efforts with applicable methods.

CHAPITRE 2

INTRODUCTION

2.1 Context

2.1.1 Overview of Climate Modeling and Seasonal Forecasting

Climate modeling is the process of using mathematical representations of the Earth's atmosphere, oceans, land surface, and ice systems to simulate and predict climate dynamics. These models are based on fundamental physical principles, such as the conservation of mass, energy, and momentum, and are implemented through numerical methods that solve complex equations governing the interactions between these systems. [1] Climate models range from global circulation models (GCMs), which simulate large-scale atmospheric and oceanic processes, to regional climate models (RCMs), which provide localized projections by incorporating finer-scale topographic and land-use details. [2] Seasonal forecasting, a subset of climate modeling, refers to the prediction of climate conditions, such as temperature and precipitation, over a period of one to six months. These forecasts rely on initial conditions (e.g., sea surface temperatures, soil moisture) and slowly varying components of the climate system, such as oceanic or atmospheric anomalies like the El Niño-Southern Oscillation (ENSO). [3] The basic principle behind seasonal forecasting is to leverage these slowly varying components, which have a predictable influence on regional weather patterns, using ensemble simulations to quantify uncertainties and provide probabilistic predictions. [4]

Seasonal forecasts play a crucial role in decision-making and planning across various sectors, including agriculture, water management, and climate risk mitigation. These forecasts provide early warnings of high-impact climate scenarios, enabling proactive decisions that result in financial savings, risk reduction, and optimized resource use. For instance, in agriculture, they assist farmers in selecting appropriate crops and determining optimal planting times based on anticipated water availability, thereby mitigating risks

1. McGuffie, K. and Henderson-Sellers, A., 2014. A Climate Modelling Primer. https://doi.org/10.1002/9781118687853
2. Flato et al., 2013. Evaluation of Climate Models. IPCC AR5 Chapter 9. https://www.ipcc.ch/report/ar5/wg1/chapter-9-evaluation-of-climate-models/
3. Doblas-Reyes, F. J., García-Serrano, J., Lienert, F., Biescas, A. P., Rodrigues, L. R., 2013. Seasonal climate predictability and forecasting : Status and prospects. https://doi.org/10.1038/ngeo1714
4. Palmer, T. N., Anderson, D. L., 1994. The prospects for seasonal forecasting—a review paper. https://doi.org/10.1256/smsqj.50402

associated with droughts or excessive rainfall. [5] Seasonal forecasts also support pre-harvest strategies, such as hedging decisions, which help shield farmers from price volatility, although their adoption is often hindered by perceptions of inaccuracy and complexity. [6] In water management, seasonal forecasts are vital for mitigating drought impacts, particularly in semi-arid regions, by enabling improved reservoir operations and efficient water allocation to reduce losses. [7] Additionally, these forecasts, when linked to hydrological models, improve predictions of water balance and inform critical decisions regarding water storage and distribution, despite occasional discrepancies between predicted and desired variables. [8] Seasonal forecasts are increasingly applied in climate risk management, where they help predict extreme weather events, providing decision-makers with tools to minimize societal and economic damages. [9] For example, accurate predictions of heatwaves or floods allow authorities to implement adaptive measures, reducing infrastructure damage and safeguarding public health. In economic sectors such as energy and water management, tailored seasonal forecasts enhance decision-making efficiency by aligning forecasts with user needs, thereby optimizing outcomes. [10] Despite their significant potential, the effectiveness of seasonal forecasts depends on their accuracy, relevance to user needs, and ease of use. Improved communication, stakeholder training, and efforts to bridge the gap between forecast complexity and user understanding are essential to maximize their utility.

2.1.2 Importance of Seasonal Climate Forecasts in MENA

Seasonal climate forecasts are critically important across the MENA region, where high temperatures, low water availability, and vulnerability to climate variability create substantial challenges for sustainable development. Forecasts provide early warnings of droughts, heatwaves, and other extreme weather events, enabling decision-makers to implement proactive measures to mitigate impacts on water resources, agriculture, and infrastructure. [11] In agriculture, these forecasts help farmers optimize crop selection and planting schedules, reducing the risks of crop failure in this water-scarce region. [12] In the water sector, seasonal forecasts guide reservoir management by predicting rainfall variability, improving water storage strategies, and ensuring more equitable water distribution. [13] With increasing climate risks, these forecasts also support disaster risk management by allowing governments to prepare for extreme events, such as heatwaves and floods,

5. Werner, M. and Linés, C., 2024. Seasonal forecasts to support cropping decisions. https://doi.org/10.5194/egusphere-egu24-13436
6. Hunt et al., 2020. Seasonal Forecast Based Preharvest Hedging. https://doi.org/10.22004/AG.ECON.309761
7. Portele et al., 2021. Seasonal forecasts offer economic benefits for hydrological decision-making. https://doi.org/10.1038/s41598-021-89564-y
8. MacLeod et al., 2023. Translating seasonal climate forecasts into water balance forecasts. https://doi.org/10.1371/journal.pclm.0000138
9. Castino et al., 2023. Towards seasonal prediction of extreme temperature indices. https://doi.org/10.5194/ems2023-590
10. Goodess et al., 2022. The Value-Add of Tailored Seasonal Forecast Information. https://doi.org/10.3390/cli10100152
11. Dunn et al., 2020. The changing climate of MENA. https://pubs.giss.nasa.gov/abs/gu00200u.html
12. Werner, M., and Linés, C., 2024. Seasonal forecasts to support cropping decisions. https://doi.org/10.5194/egusphere-egu24-13436
13. Portele et al., 2021. Seasonal forecasts for hydrological decision-making. https://doi.org/10.1038/s41598-021-89564-y

which are becoming more frequent in the region due to climate change.[14] Moreover, the economic benefits of using seasonal forecasts are significant. By enabling energy companies to anticipate peak demand periods driven by heatwaves, and by helping municipalities optimize water usage during droughts, these forecasts provide cost savings and efficiency gains.[15] However, challenges persist in ensuring the accuracy and usability of these forecasts. The arid and semi-arid nature of much of the MENA region, coupled with complex interactions between regional climate drivers, makes it difficult to provide highly localized forecasts.[16] Addressing these challenges through improved modeling techniques and stakeholder engagement will be critical to maximizing the value of seasonal forecasts in the MENA region, ensuring better preparedness and resilience against a changing climate.

2.2 Objectives of the Work and Description of Report Content

The primary objective of this work is to evaluate the effectiveness of climate models, focusing specifically on their performance in predicting key climate variables such as temperature, precipitation. This evaluation incorporates both deterministic and probabilistic approaches to identify the most skillful models and their suitability for practical applications.

2.2.1 Specific aims of evaluating deterministic and probabilistic models.

The evaluation of deterministic and probabilistic models is essential for understanding their unique strengths, limitations, and potential applications in diverse fields. Deterministic models, which generate a single, precise outcome based on initial conditions, are widely used when exactness and reproducibility are critical, such as in engineering and physical simulations.[17] Their evaluation focuses on assessing accuracy and reliability under specific conditions, providing clarity in cause-and-effect relationships. In contrast, probabilistic models incorporate uncertainty by assigning probabilities to various potential outcomes, enabling the representation of real-world complexities and variability.[18] These models are particularly beneficial for strategic planning and risk management, where understanding a range of possible scenarios is crucial. The evaluation of both types of models includes conducting sensitivity analyses to determine how changes in input variables affect outcomes, which helps in identifying key drivers of uncertainty and improving model performance.[19] Additionally, risk assessment is a vital component, with deterministic approaches offering

14. Castino et al., 2023. Towards seasonal prediction of extreme temperature indices. https://doi.org/10.5194/ems2023-590

15. Goodess et al., 2022. Value-Add of tailored seasonal forecast information. https://doi.org/10.3390/cli10100152

16. Latif et al., 2011. ENSO predictability and regional climate impacts. https://doi.org/10.1175/2010JCLI3405.1

17. McGuffie, K., and Henderson-Sellers, A., 2014. *A Climate Modelling Primer*. Wiley. https://doi.org/10.1002/9781118687870

18. Palmer, T., and Hagedorn, R., 2006. *Predictability of Weather and Climate*. Cambridge University Press. https://doi.org/10.1017/CBO9780511617652

19. Seneviratne, S.I., et al., 2021. *Metrics for climate model evaluation : A review*. Nature Communications. https://doi.org/10.1038/s43247-021-00094-x

straightforward estimations for defined scenarios, while probabilistic approaches address uncertainties by simulating a spectrum of possible outcomes.[20] These evaluations also aim to support decision-making processes by identifying which type of model is more appropriate for specific contexts—deterministic models for precise predictions and probabilistic models for flexible planning under uncertainty.[21] Finally, probabilistic models are often recognized for their adaptability in dynamic environments, as they can incorporate new data and adjust probability distributions to reflect evolving conditions, making them indispensable for complex systems where deterministic models may fall short.[22] Together, the evaluation of deterministic and probabilistic models provides invaluable insights into their suitability for addressing specific challenges, supporting informed decision-making, and advancing model development.

2.2.2 Description of Content

This report is designed to provide a comprehensive analysis of climate model evaluation, focusing on both deterministic and probabilistic approaches. The structure of the report follows a logical progression, starting with an introduction to the fundamental concepts behind climate models. The first section lays the groundwork for understanding the key differences between deterministic and probabilistic models, describing how each approach is used to simulate climate systems and predict future outcomes. The methodology chapter follows, detailing the specific techniques employed to assess the models. This includes the use of both deterministic and probabilistic metrics such as Root Mean Square Error (RMSE), Anomaly Correlation Coefficient (ACC), and Brier Score, which are critical for evaluating the models' accuracy and performance in predicting climate variables like temperature and precipitation.

Next, the report moves on to the results and analysis, where the performance of the selected models is presented and compared. This section highlights the models' strengths and weaknesses, providing insight into how well they predict climate patterns across various geographical regions and time periods. Special attention is given to the models' skill in forecasting extreme weather events, which are particularly relevant to sectors like agriculture, water resource management, and disaster risk reduction.

The final section of the report provides conclusions and recommendations based on the analysis. This chapter synthesizes the findings, offering practical suggestions for improving the accuracy, usability, and application of climate forecasts. Recommendations also address how future developments in climate modeling can better meet the needs of decision-makers and stakeholders. The report as a whole seeks to contribute valuable insights into the ongoing development of climate prediction systems, aiming to enhance their effectiveness in real-world applications.

20. PreventionWeb, 2021. *Deterministic and Probabilistic Risk*. https://www.preventionweb.net/understanding-disaster-risk/key-concepts/deterministic-probabilistic-risk

21. Goodess, C.M., et al., 2022. *The Value-Add of Tailored Seasonal Forecast Information for Industry Decision Making*. Climate. https://doi.org/10.3390/cli10100152

22. Latif, M., and Keenlyside, N., 2011. *El Niño/Southern Oscillation Predictability*. Journal of Climate. https://doi.org/10.1175/2010JCLI3405.1

CHAPITRE 3

LITERATURE REVIEW

3.1 Overview of Climate Models

3.1.1 Deterministic Models

Deterministic models rely on mathematical equations that describe the physical processes of the atmosphere. These models use fixed initial conditions to provide precise predictions, making them suitable for short-term forecasting. However, due to the chaotic nature of atmospheric systems, as demonstrated by Lorenz's theorem, deterministic models are limited in their ability to predict long-term outcomes. Small errors in initial conditions can lead to significant differences in results, reducing their reliability for seasonal or long-term forecasting. [1]

Deterministic climate models operate based on fixed initial conditions and mathematical equations that simulate physical processes in the atmosphere. These models are particularly useful for short-term predictions as they provide precise and singular forecasts. However, deterministic models are significantly limited when forecasting over extended periods. This limitation arises due to the inherent sensitivity of atmospheric systems to initial conditions—a concept known as the *butterfly effect*, introduced by Edward Lorenz in 1963. His research demonstrated that even minute changes in the initial conditions of a system could lead to vastly different outcomes over time, emphasizing the chaotic nature of weather systems.

For seasonal forecasting, deterministic models often fail because minor errors in the initial conditions can amplify, resulting in inaccurate predictions for longer timescales. Despite these challenges, deterministic models are vital for understanding specific phenomena over shorter durations with high spatial and temporal resolution.

3.1.2 Probabilistic Models

Probabilistic models address the limitations of deterministic approaches by incorporating uncertainty into forecasts. Instead of producing a single outcome, these models generate a range of possible scenarios, each with an associated probability, using ensemble simulations or statistical techniques. This makes probabilistic models particularly useful for medium-

1. Lorenz, E. N. (1963). Deterministic Nonperiodic Flow. *Journal of the Atmospheric Sciences, 20*(2), 130–141.

to long-term forecasts and risk assessment in climate-sensitive sectors such as agriculture, water management, and disaster mitigation. [2]

The evaluation of probabilistic models relies on metrics that assess their ability to represent uncertainty and provide actionable insights :

— **Reliability :** Measures how well predicted probabilities align with observed frequencies.
— **Resolution :** Assesses the model's ability to distinguish between different outcomes.
— **Discrimination :** Evaluates the model's ability to separate events from non-events. [3]

Probabilistic models are especially valuable for decision-making under uncertainty, as they provide stakeholders with a clearer understanding of risks and potential scenarios, enabling proactive measures to mitigate impacts.

Comparison of Deterministic and Probabilistic Models

Deterministic and probabilistic models serve complementary roles in climate modeling and forecasting. Their distinct features and applications are summarized in Table **??**.

TABLE 3.1 – Comparison of Deterministic and Probabilistic Models

Feature	**Deterministic Models**	**Probabilistic Models**
Predictability	Produces a single fixed outcome based on initial conditions	Generates a range of outcomes with associated probabilities
Sensitivity to Initial Conditions	Highly sensitive, leading to reduced accuracy over long timeframes	Less sensitive due to ensemble techniques reducing error amplification
Application Domain	Suitable for short-term, high-resolution tasks, e.g., extreme event analysis	Ideal for medium- and long-term decision-making under uncertainty
Use of Historical Data	Limited emphasis on historical variability	Extensively relies on historical data for statistical projections
Examples	Global Circulation Models (GCMs), Regional Climate Models (RCMs)	Ensemble forecasting, statistical downscaling

While deterministic models are preferred for precise and short-term predictions, probabilistic models provide critical insights into the likelihood of various scenarios, making them indispensable for managing climate-related risks.

2. World Meteorological Organization (2024). *Guidance on Verification of Operational Seasonal Climate Forecasts*. https://library.wmo.int/records/item/56227-guidance-on-verification-of-operational-seasonal-climate-forecasts
3. Rapport de projet 2024–2025, *3rd Year Meteorology Modeling Project*.