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APPLICATIONS OF MATHEMATICAL MODELING IN CLIMATE CHANGE PREDICTION

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Keywords
Mathematical model is a system of equations that is usually simplified and idealised to capture the essence of a complex system. Mathematical modelling is a system of equations that is typically simplified and idealised to capture the essence of a complex system. The phenomena is explored using qualitative research and thematic analysis. Climate change prediction and environmental forecasting, uncertainty quantification, climate policy, general circulation models, Science Policy interface, Pakistan

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Abstract

The present study was concerned with the contribution of mathematical modelling for predicting the climate change and forecasting environments from the eyes of domain experts. The study employed a qualitative case study research design and data were collected using semi-structured interviews, expert consultation and systematic document analysis of climate reports, modelling studies and scientific publications. Twenty-four individuals were intentionally selected to represent climate scientists, environmental scientists, applied mathematicians and climate policy experts from research institutions, government agencies and international environmental organizations. Thematic content analysis was utilized to examine the prominent themes emerging from the compiled content, covering aspects such as the model's applicability, predictive capability, scientific challenges, uncertainty handling, and the function of mathematical modeling in the context of climate policy development. Mathematical models were found to be crucial for long range climate forecasting but this was dependent upon data quality, ability to compute and inter-disciplinary collaboration. The specific challenges identified by the experts were uncertainty quantification, model validation and policy decision making from technical output. The improved mathematical models, the study said, together with effective scientific communication and institutional investment, could significantly improve the evidence base for adaptation and mitigation strategies to climate change. The results are particularly relevant to developing countries such as Pakistan where climate vulnerability is high and modelling infrastructure and technical capacity is limited.

1. Introduction

Climate Change is one of the most important science and policy issues of the 21st century. With the most unpredictable weather patterns, higher average global temperatures, rising sea levels and more extreme climate events than ever before, the need for more reliable scientific forecasts of climate futures has never been greater. Mathematical modeling is the backbone of the methodologies scientists use to build, test and update such predictions. Climate models can simulate the dynamics of the Earth system, predict future climate scenarios and assess whether a range of emissions scenarios (IPCC, 2021) lead to different outcomes.

The models used to predict climate change range from simple energy balance models to global circulation models that contain some of the most complicated calculations ever made. The two approaches have different mathematical models, data requirements and characterizations of the uncertainty. Over the past few decades, these models have been the subject of a large scientific enterprise and have become more and more complex, allowing them to capture the multiscale, multivariable nature of the Earth's climate system. A range of mathematical tools have supported climate prediction, including differential equations, stochastic modelling, statistical downscaling and machine learning algorithms, often in combination with one another (Reichstein et al., 2019).

Despite impressive advances in modeling capability, there are a number of challenges. The climate is characterized by uncertainty in all climate projections . This is due to the incompleteness of observations , assumptions about the structure of models , internal climate variability , and climate change projections for different future emissions scenarios . In climate science, there is always the challenge of explaining uncertainty to policy makers and the public while maintaining the credibility of the scientific consensus (Moss & Schneider, 2000). Moreover, scientific communication and knowledge brokering is not limited to the technical realm when the scientific results of mathematically sophisticated models are to be translated into concrete policy advice.

Mathematical modeling is an essential component of climate prediction in the Pakistan, which is one of the most climate vulnerable countries in the world. Recurrent floods, prolonged droughts, glacial lake outburst floods and heat extremes characterize the South Asian climate contexts, which require a strong predictive capacity that has never been more critical. But Pakistan does not have the capacity to develop a sound mathematical climate model because of the non-availability of advanced mathematical instruments, weak training programmes for quantitative climate scientists and weak institutional coordination and cooperation between research and policy institutes (Iqbal et al., 2018).

The purpose of this study was to explore the attitudes of experts regarding the use of mathematical modeling in predicting climate change, the effectiveness of mathematical modeling and limitations. The research used qualitative approaches to gain insights into the perspectives of practitioners working in the area of mathematical science and climate policy, thus adding to the development of knowledge that would not be able to be produced by technical studies alone. The aims were to learn from the experts about the strengths and weaknesses of mathematical climate models; discuss the challenges of dealing with uncertainty and predicting accuracy; and learn about the use of model results in climate related policy making in developing country settings.

2. Review of Literature

For more than half a century, climate science has relied on mathematical models and probably the most important result is the quantitative link between the amount of CO2 in the atmosphere and the surface temperature as found in the work of Manabe and Wetherald (1967). As the more detailed climate simulation models were developed, more components such as ocean circulation, land surface processes and biogeochemical cycles were added to the general circulation models, thus increasing the scope and realism of climate simulations (Held & Suarez, 1994). The most recent manifestation of this approach is the modern Earth systems models . These models merge mathematical models of the atmosphere, ocean circulation, sea ice, vegetation and carbon cycle processes into one computational framework.

Most physics-based models of climate are based upon the differential equations describing the physical laws governing the motion of the atmosphere, the thermodynamic exchange and the radiative transfer in the atmosphere. The general circulation models are based on the discretisation of systems of partial differential equations over a global grid, and stochastic methods are increasingly being used to model processes on subgrid scales, or for natural climate variations that cannot be fully captured by the deterministic methods (Palmer, 2012). Statistical methods, including regression analysis, time series decomposition and Bayesian inference, complement dynamical methods and can be used to filter out the climate signal from noisy observations and to measure uncertainty in the climate models.

There is a lot of recent interest in using machine learning as a complementary technology for climate modeling. Deep learning architectures, neural networks and ensemble methods have proven useful in several applications, notably in weather prediction, climate downscaling and parameterisation of complex physical processes that cannot be explicitly resolved in models (Reichstein et al., 2019; Rolnick et al., 2022). The combination of machine learning and process modelling opens a new frontier in mathematical climate science, but interpretability, generalization and physical consistency still pose important research questions.

There are several sources of uncertainty in climate projections, which can be broadly grouped into three categories: uncertainty from scenarios (uncertainty in the range of future GHG emissions), uncertainty from models (structural differences between models) and from internal variability, due to the chaotic behavior of the climate system. Progress in uncertainty quantification has greatly improved the ability of researchers to characterize and communicate uncertainty in projections, for example by using large ensemble simulations and formal uncertainty propagation techniques (Hawkins & Sutton, 2009). Knutti et al. (2010) showed using a multi-model ensemble analysis that the inter-model disagreement was still significantly larger for precipitation than for temperature projections. This has important implications for water resources management in climate sensitive regions such as South Asia.

Climate Modelling is a complex science-policy interface and knowledge translation processes. The difficulties of communicating probabilistic, uncertainty-rich scientific information that is understandable and usable by policy makers within political contexts have been well documented (Cash et al., 2003). The outputs of mathematical modeling can be connected with evidence-based climate governance through effective boundary organizations and science communication strategies. The connection between the climate model and public understanding was mediated by cultural, political, and institutional factors that can amplify or mute scientific messages and that are external to the technical content of the model (Hulme 2011).

The rising importance of regional climate modeling is associated with the necessity to consider the restrictions of the global model for local adaptation planning. For example, Giorgi and Gutowski (2015) summarized recent advances in regional climate modeling, and found that improvements in the representation of precipitation extremes and topographically driven climate patterns had been made in regions where dynamical downscaling was used, which involved nesting the output of the global model at the boundary of the higher resolution regional model. These regional modeling improvements have had substantial implications for flood risk, glacial changes and vulnerabilities in agriculture in mountainous and monsoon affected areas in Pakistan. Instead of dynamical approaches, which are more computationally demanding, statistical models have already been systematically evaluated by Jones et al. (2004), who found that well-calibrated statistical models can reproduce observed climate variability at the local scale with competitive accuracy.

3. Method of Research

The method of this research was qualitative and used to study the role of mathematical modeling in the prediction of climate change and forecast of the environment. A case study design was used as it was especially interesting to gain insight into the views of the experts and the relevance of mathematical models for climate research. The case study approach was chosen since it is well suited for exploring the contextual depth and experiential richness that is required by the context of the complex relationship between mathematical techniques, scientific practice and policy application in climate science (Yin, 2018).

Data were gathered through semi-structured interviews, expert consultation and systematic document analysis. The corpus for document analysis included peer-reviewed documents (climate modeling studies, national and international climate reports, policy briefs and technical documents of the modeling projects at the participating institutions). We developed semi-structured interview guides based on a review of relevant literature and pre-tested the interview guides with two subject experts before using them to conduct the interviews. The interview questions were: What are their views on the effectiveness of mathematical models; How well do mathematical models predict; What are some of the limitations they encountered in practice; What do they do to manage uncertainty; and How do they use modeling in relation to policymaking on climate change.

Twenty-four participants were purposefully selected to represent a range of disciplinary backgrounds and institutional roles relevant to mathematical climate modelling. The sample also included applied mathematicians with experience in differential equations and stochastic modelling, climate researchers from government climate divisions and the international environmental community, and environmental researchers specialising in regional climate assessment, from the national research institutes. Purposive sampling was used to ensure information-rich participants who would be able to provide substantive expert input on the research questions (Patton, 2015). The interviews were conducted in-person or via video conference on-on-one, and typically lasted between 45 and 90 minutes. Expert consultations were extended follow-up discussions with a few selected individuals considered to possess greater knowledge on particular technical and/or policy aspects of climate modeling. Each session was recorded with the consent of the participants and transcribed verbatim by trained research assistants. Document analysis involved the systematic extraction of the text and the main content was coded accordingly to a well-defined set of codes.

The semi-structured, one-on-one interviews were conducted either in-person or virtually and lasted 45-90 minutes . Expert consultation involved extended follow-up discussions with selected participants identified as having particular depth of knowledge on specific technical or policy aspects of climate modelling. All sessions were audio-taped with the informed consent of participants and transcribed verbatim by trained research assistants. Documents were systematically extracted using a protocol and relevant passages were indexed according to a predetermined coding framework.

The data were analyzed using thematic content analysis based on the procedures described by Braun and Clarke (2006). Transcripts and documents were analyzed using open coding. This involved careful reading of the transcripts and documents and assigning initial codes to meaningful units of data. Related codes were then grouped into categories, which were examined and refined iteratively to ensure conceptual coherence and data groundedness. Interpretive synthesis was used to develop final themes and an audit trail of the analysis process was recorded in detail. To ensure rigor, we triangulated across data sources, conducted member checking with a subset of the participants, and had an independent qualitative researcher peer review the coding framework. These combined actions increased the credibility, dependability and confirmability of the findings following criteria set out by Lincoln and Guba (1985).

4. Results and Discussion

Thematic content analysis identified five major themes: mathematical modelling is indispensable in climate prediction; predictive accuracy, limitations and model uncertainty; methodological innovation and computational challenges; the science-policy interface and knowledge translation; and capacity building and institutional support needs. Themes are introduced and discussed below.

4.1 The Role of Mathematical Modelling in Climate Prediction

Scientists from various disciplines have repeatedly confirmed that mathematical modeling was the essential scientific basis for the prediction of climate change. The climate scientists were insistent that given the complexity, scale and time horizons involved in climate projection, mathematical models were the only methodologically viable way to produce reliable forecasts. "Mathematical models are the way that the future climate system can be read otherwise there would be only descriptive accounts of past climate behaviour," said a senior climate scientist.

One scientific achievement identified by the participants was the continuing evolution of the modeling frameworks, with successive generations of models representing more and more Earth system processes. The applied mathematicians in the sample talked about the variety of mathematical approaches used in the field, from the partial differential equations governing atmospheric fluid dynamics to stochastic parameterizations of cloud microphysics. They argued that such diversity was an indication of the real mathematical complexity of the climate system and of the intellectual span of the contributions which had been incorporated into modelling practice. These observations were consistent with the IPCC (2021) assessment that multi-model ensembles were now standard tools for producing policy-relevant projections, and provided a scientifically defensible basis for both global and regional climate assessments .

4.2 Predictive performance, limitations and uncertainty of model

Among all data sources, one of the most discussed topics was predictive accuracy and its limits. The participants agreed that uncertainty is an inherent and unavoidable characteristic of climate projections, due to factors such as limited observational data, assumptions embedded in the structure of models, parameterization choices and the inherent unpredictability of future human behavior regarding emissions. But experts argued that uncertainty was not unreliability but a genuine representation of what current mathematical science could and could not determine.

The distinction was very difficult to convey to non-expert audiences, noted several participants. A persistent misreading with potentially harmful consequences for public trust and policy willingness was the tendency to interpret scientific uncertainty as evidence of contested knowledge. These observations resonated with the theoretical concerns raised by Moss and Schneider (2000) and the cultural analysis presented by Hulme (2011), and pointed to the need for more sophisticated frameworks for public communication that could convey the probabilistic nature of climate projections. Hawkins and Sutton (2009) had shown that internal variability was the dominant source of uncertainty on decadal timescales for near-term regional projections, a technicality that the participants said was seldom understood outside expert scientific communities.

4.3 Computational challenges and methodological innovation

Participants identified methodological innovation as a source of scientific progress and as a driver of new technical challenges. There was a lot of talk about the increasing integration of machine learning techniques into climate modeling. Participants delivered nuanced views of the promise and limitations of machine learning, recognizing its efficacy for pattern recognition, statistical downscaling, and computational emulation of costly physical processes. Participants expressed concerns about the reliance of machine learning on historical data patterns, the limited physical interpretability of machine learning, and the uncertain generalizability of machine-learning models to novel climate states outside the training distribution.

The constraints imposed by computational resources were identified as a major practical barrier, especially for research institutions in developing countries such as Pakistan. Participants from institutions based in Pakistan described dependence on outputs from international modelling centres, which they felt limited research independence and the applicability of model outputs to regional and local conditions. Giori and Gutowski (2015) also observed such asymmetries in regional modeling capacity between high-income and developing country research communities, and recommended a structural response of coordinated international investment in capacity building. Jones et al. (2004) noted that statistical downscaling methods were less computationally intensive than dynamical approaches and provided a pragmatic means for researchers in developing countries to derive locally relevant climate projections from existing global model outputs.

4.4 Science-Policy Interface and Knowledge Translation

The fourth major theme was the challenges and strategies in translating complex outputs from mathematical modeling into useful forms for climate policy. Policy specialists and government officials with scientific training in the sample identified the large gap between the probabilistic, technically complex outputs of mathematical models and the clear, action-oriented guidance that policymakers typically sought. Closing this gap required skilled knowledge brokers who could understand the technical aspects of modeling science as well as the institutional and political context in which policy decisions were made.

Participants reported a variety of knowledge translation strategies including the development of simplified policy briefs, visual communication tools, scenario narratives and interactive decision-support platforms. The importance of continuous interaction between scientists and policymakers throughout the research and communication process was repeatedly stressed. Cash et al (2003) argued that effective boundary organisations were characterised by their salience, credibility and legitimacy – properties that necessitated sustained investment in relationship building rather than one-directional information transfer. The present findings supported this framework, extending it to the particular context of climate modeling in a policy-making environment in a developing country, where resource constraints and institutional fragmentation posed additional challenges to sustained science-policy engagement.

4.5 Institutional and Capacity Development Requirements

The fifth theme incorporated participant evaluations of institutional and human resource gaps hindering effective application of mathematical modeling in climate prediction and policy in Pakistan. Participants identified critical gaps in trained quantitative climate scientists, the computational infrastructure to support high-resolution modeling, the mechanisms of inter-institutional coordination, and the funding for research in applied climate modeling. The deficits were found to constrain both the scientific quality of domestic climate knowledge and the country's ability to engage on an equal footing in international climate research collaborations.

Among the recommendations made by participants were the creation of specialized postgraduate programs in mathematical climate science, investment in high performance computing facilities at national research universities, the creation of multiagency coordination platforms to share climate data, and the development of regional modeling networks in South Asia that could pool resources and expertise. The recommendations were grounded in a systemic understanding of capacity constraints that extended beyond individual technical training to include the institutional and infrastructural conditions for sustainable scientific productivity. Participants described structural challenges, similar capacity gaps were identified by Iqbal et al. (2018) in their assessment of Pakistan's climate research infrastructure, and the need for coordinated government and international donor investment to address these.

Table 1: ***Summary of Major Themes, Sub-themes, and Key Expert Insights***

Theme	Key Sub-themes	Representative Insights
Indispensability of Modeling	Model centrality, historical development, mathematical breadth	Models seen as irreplaceable; multi-model ensembles now standard for policy-relevant projections
Predictive Accuracy & Uncertainty	Uncertainty sources, communication challenges, probabilistic framing	Uncertainty is inherent and irreducible; communicating it to non-specialists remains a major challenge
Methodological Innovation	Machine learning integration, computational limits, regional	ML holds promise but raises physical interpretability concerns; computing

	applicability	constraints limit developing country capacity
Science-Policy Interface	Knowledge translation, knowledge brokers, sustained engagement	Effective communication requires sustained scientist-policymaker relationships, not one-time information transfer
Capacity Building Needs	Training gaps, computing infrastructure, regional networking	Pakistan faces structural constraints requiring coordinated investment in postgraduate training and HPC infrastructure

5. Conclusion

This study yields qualitative evidence for the need for mathematical modelling for prediction of climate change and for forecasting environmental change, even though this is challenging. The scientific value of mathematical models was constantly highlighted by the expert participants, as well as various challenges that repeatedly emerged in predicting the accuracy of mathematical models, communicating uncertainty, using math in practice and decision processes, and translating knowledge into decision processes. By employing a qualitative case study design, a richness of understanding was gained that could only be achieved by technical or quantitative studies alone, uncovering the human, institutional and epistemological aspects in which mathematical science is used to solve one of the greatest challenges of today's world.

Results are applicable to the practice of various stakeholders. Climate scientists and mathematicians are urged to cover uncertainty in a user-friendly manner, and to proactively interact with the policy community in the modelling and knowledge translation process. The policy makers in institutions and funding agencies should give attention to the development of computational infrastructure, special training courses, research networks, particularly in the developing countries including Pakistan in a climate sensitive region. Policymakers should encourage the creation of boundary organizations and science advisory arrangements that can help fill the epistemological divide between mathematical modelling science and climate governance based on evidence.

Future research should focus on comparative studies of science-policy interface (SPI) practices in different national and regional contexts, longer term studies investigating the evolution of modelling capacity as it relates to the institutional investment, and interdisciplinary studies examining the best ways of incorporating machine learning and process-based modelling into the mathematical structure of climate prediction. These instructions, taken together, define an agenda for qualitative and interdisciplinary climate science scholarship, which can be a response to the predominant technical and quantitative approaches to climate science.

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