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DISSERTATION

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The Concept of Nature in Climate Computational Models: A Philosophical Inquiry

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CERTIFICATE

This is to certify that the dissertation entitled **"The Concept of Nature in Climate Computational Models: A Philosophical Inquiry"** submitted by **Mehul Jhunjhunwala**, Roll No. **20221428**, in partial fulfillment of the requirements for the award of the degree of **Bachelor of Science (Honours) Computer Science** of University of Delhi, is a record of the candidate's own work carried out by him/her under my supervision and guidance.

The matter embodied in this dissertation is original and has not been submitted for the award of any other degree or diploma.

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ABSTRACT

Climate computational models are central to contemporary environmental governance, shaping policy decisions, public understanding, and scientific discourse. These models, however, do more than simulate atmospheric or ecological systems,they actively construct representations of "nature" that influence how societies perceive, respond to, and prioritize climate action.

This dissertation offers a philosophical inquiry into the conceptualization of nature embedded within climate computational models, exploring how abstraction, quantification, and algorithmic simplification mediate human-environment relationships. Drawing from philosophy of science, epistemic justice, and environmental humanities, it critically examines how model structures privilege certain forms of knowledge,often marginalizing localized, indigenous, and experiential understandings of nature,and how these exclusions impact ethical decision-making.

The study further interrogates the political and economic forces that shape modeling practices, including the influence of corporate interests and funding networks that subtly or overtly steer climate narratives.

By analyzing the representational choices, uncertainties, and normative assumptions within computational frameworks, this inquiry aims to develop a conceptual foundation for integrating plural epistemologies and fostering more inclusive, accountable, and ethically grounded modeling practices.

The dissertation concludes by proposing theoretical principles for responsible climate modeling that recognize the complexity of nature, the diversity of human knowledge, and the moral stakes involved in translating ecological realities into computational abstractions.

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Chapter 1

INTRODUCTION

1.1 Background

Climate change is widely recognized as one of the most pressing global challenges of the 21st century, affecting ecosystems, economies, and human well-being across the world. In response, computational climate models have become essential tools for understanding environmental processes, predicting future scenarios, and informing policy decisions. These models, which rely on complex algorithms, large datasets, and mathematical abstractions, are used by scientists, governments, and international bodies to assess risks, design mitigation strategies, and allocate resources.

However, the reliance on computational representations of climate systems brings forth a series of conceptual, ethical, and political concerns. Climate models are not merely passive tools; they actively shape how nature is defined, measured, and communicated. The abstraction and quantification processes inherent in modeling require simplification, assumptions, and selection of data that reflect particular scientific, institutional, and socio-political priorities. As a result, certain forms of knowledge, especially localized, indigenous, or experiential understandings of nature can be marginalized or excluded altogether.

Moreover, the construction and dissemination of climate models are influenced by broader power structures, including corporate interests, funding networks, and political agendas. These forces can subtly steer modeling practices and the interpretation of results, contributing to narratives that obscure unequal responsibilities or reinforce dominant perspectives. This raises critical questions about epistemic justice, representation, and accountability in climate science and governance.

Given the growing reliance on computational models to guide global responses to climate change, it becomes imperative to reflect on how these models conceptualize nature, whose knowledge is privileged or silenced, and how power dynamics influence the framing of environmental issues. This dissertation seeks to explore these challenges through a philosophical lens, offering conceptual tools to understand, critique, and ultimately improve the ways in which computational models engage with the complexity of nature and human knowledge.

1.2 Problem Statement

Climate computational models have become indispensable tools for forecasting environmental change and informing climate policy. However, beyond their technical function, these models play a formative epistemic role: they actively construct representations of "nature" through processes of abstraction, quantification, and algorithmic simplification. These representational practices do not merely describe natural systems but shape how ecological phenomena are defined, interpreted, and rendered actionable within scientific and policy frameworks.

The central problem addressed in this dissertation is that the conceptualization of nature embedded within climate computational models systematically privileges particular epistemic frameworks while marginalizing others. In translating complex ecological realities into formalized, computational structures, modeling practices tend to favor quantifiable, standardized, and globally scalable forms of knowledge. As a consequence, localized, indigenous, and experiential understandings of nature are often rendered peripheral, incommensurable, or epistemically invisible within dominant modeling paradigms.

This core representational problem is further structured and reinforced by broader institutional and socio-political conditions under which climate models are developed and deployed. Factors such as funding regimes, corporate and governmental priorities, and the circulation of strategic misinformation shape research agendas, modeling assumptions, and interpretive narratives. While these forces do not determine model outcomes in a simple or deterministic manner, they influence which forms of knowledge gain epistemic authority and which remain excluded, thereby amplifying existing power asymmetries in climate governance.

Accordingly, this dissertation investigates how abstraction, institutional context, and epistemic power interact within climate computational modeling to shape representations of nature and their downstream ethical and political consequences. By critically examining these dynamics, the study aims to develop theoretical principles that support more plural, reflective, and accountable approaches to climate modeling,approaches that acknowledge epistemic diversity while maintaining scientific rigor and policy relevance.

1.3 Research Objectives

The primary objective of this dissertation is to critically examine how climate computational models conceptually construct representations of nature through processes of abstraction, quantification, and algorithmic simplification. Building on this core concern, the study seeks to develop a philosophical framework for analyzing the epistemic, ethical, and institutional dimensions of climate modeling, with particular attention to how certain forms of knowledge are marginalized while others are privileged.

Specifically, the research aims to:

- Analyze how abstraction, quantification, and algorithmic simplification operate as epistemic practices in climate computational models, shaping how ecological systems are defined, interpreted, and rendered actionable within scientific and policy contexts.

- Examine how dominant modeling paradigms tend to privilege standardized and quantifiable forms of knowledge, while marginalizing or excluding localized, indigenous, and experiential epistemologies, and assess the ethical implications of these representational asymmetries.

- Investigate how institutional and socio-political conditions,such as funding regimes, corporate and governmental priorities, and dominant scientific norms,structure modeling assumptions and interpretive frameworks, thereby influencing which representations of nature acquire epistemic authority.

- Develop a philosophical and conceptual framework that enables critical engagement with the assumptions embedded in climate computational models and supports more reflective, plural, and accountable approaches to climate modeling.

- Articulate normative principles to guide the responsible development and use of climate computational models, emphasizing epistemic diversity, ethical representation, and scientific rigor without advancing prescriptive or speculative policy interventions.

Through these objectives, the dissertation aims to contribute to interdisciplinary debates at the intersection of computer science, philosophy of science, and climate governance by clarifying the ethical and epistemic stakes involved in translating complex ecological realities into computational representations.

1.4 Research Questions

Guided by the central problem of how climate computational models conceptually construct representations of nature, this dissertation addresses the following research questions:

1. How do abstraction, quantification, and algorithmic simplification function as epistemic practices in climate computational models, and how do they shape the representation and framing of ecological systems?

2. What modeling assumptions, representational choices, and methodological conventions contribute to the ecological narratives embedded within climate computational frameworks?

3. In what ways are marginalized epistemologies,including indigenous knowledge, localized ecological practices, and experiential understandings,excluded, undervalued, or rendered incommensurable within dominant climate modeling paradigms, and through what mechanisms does this exclusion occur?

4. How do institutional and socio-political conditions, such as funding regimes, corporate and governmental priorities, and the circulation of strategic misinformation, structure model design, interpretation, and dissemination, thereby influencing which representations of nature acquire epistemic authority?

5. How do these representational and institutional dynamics contribute to forms of epistemic injustice, including the reinforcement of unequal power relations, the obscuring of responsibility, and the marginalization of vulnerable communities in climate governance?

6. What conceptual and normative principles can guide the development and use of climate computational models that are epistemically plural, ethically reflective, and accountable, while maintaining scientific rigor and policy relevance?

1.5 Research Methodology Overview

This dissertation adopts a conceptual and philosophical methodology to examine how nature is represented within climate computational models and how these representations are shaped by epistemic, political, and ethical forces. The study does not involve empirical experimentation or data collection; rather, it systematically analyzes the assumptions, frameworks, and socio-political influences underlying existing modeling practices. The methodology is structured around the following key approaches:

1. **Philosophy of Science Analysis:** The study begins by investigating how abstraction, quantification, and algorithmic processes influence the construction of scientific knowledge. It draws from philosophical discussions on modeling, representation, uncertainty, and objectivity to explore the ways computational climate models define and interpret ecological systems. The aim is to critically assess how formal methods, parameter selection, and mathematical approximations impact the portrayal of nature.

2. **Epistemic Justice Framework:** A central component of the methodology is the application of epistemic justice theory to examine which forms of knowledge are legitimized or excluded. By engaging with philosophical literature on marginalized epistemologies, the dissertation analyzes how local, indigenous, and experiential knowledges are sidelined within dominant modeling paradigms. This approach helps reveal structural injustices embedded in computational frameworks.

3. **Critical Discourse and Political Economy Inquiry:** The research investigates the broader socio-political context influencing model construction and interpretation. Drawing from political philosophy, science and technology studies (STS), and environmental humanities, it examines how corporate interests, misinformation campaigns, and funding structures affect scientific outputs. This component considers how algorithmic models may be shaped to favor particular narratives and obscure responsibility.

4. **Normative Ethical Analysis:** The dissertation further engages with ethical theories to evaluate the responsibilities of model developers, policymakers, and scientific institutions in representing climate phenomena. It explores how ethical principles such as fairness, accountability, and transparency can guide modeling practices, particularly in scenarios where scientific knowledge intersects with global inequality and environmental justice concerns.

5. **Theoretical Framework Development:** Based on the insights from the above analyses, the dissertation proposes a conceptual framework for integrating plural epistemologies into computational climate models. This framework emphasizes interpretability, inclusive participation, and reflexivity in modeling practices while safeguarding scientific rigor and policy relevance.

1.6 Scope and Limitations

1.6.1 Scope

This research focuses on:

- A conceptual analysis of abstraction, quantification, and algorithmic processes in climate models, with a focus on how these influence the framing of ecological systems.
- An examination of epistemic exclusions, particularly the marginalization of indigenous, localized, and experiential knowledge, drawing from theories of epistemic justice.
- A critical discussion of socio-political factors, including corporate influence, misinformation campaigns, and structural inequalities, and how these forces affect the design, interpretation, and dissemination of climate models.
- The development of a philosophical framework that integrates plural epistemologies and fosters ethical reflection on the role of computational models in climate governance.
- To support its arguments, the dissertation will reference existing case studies, scholarly works, and historical examples rather than conducting original simulations or algorithmic modeling.

Technical aspects of climate models, such as their mathematical structures and computational methods, will be discussed as contextual background but will not be the primary focus of inquiry.

1.6.2 Limitations

The research has the following limitations:

- The absence of empirical research or expert interviews, which restricts the ability to validate claims through primary data. The analysis will rely exclusively on secondary sources, including published research and publicly available information.
- The focus on conceptual and normative critique rather than actionable, prescriptive guidelines. While ethical challenges and injustices will be examined, the dissertation will refrain from proposing speculative policy interventions or untested frameworks.

- Time constraints and scope boundaries, as the study will cover selected examples and representative cases rather than attempting an exhaustive survey of all modeling practices or geopolitical contexts.

Despite these limitations, the dissertation seeks to offer a rigorous, interdisciplinary contribution that is grounded in theoretical inquiry and open to dialogue across fields. By highlighting the epistemic and ethical stakes involved in computational representations of nature, it aspires to inform ongoing conversations in computer science, environmental governance, and beyond.

1.7 Contributions

The main contributions of this research include:

1. **A Critical Examination of Modeling Practices:** By analyzing abstraction, quantification, and algorithmic simplification, this research offers a thorough critique of how computational models frame nature and environmental phenomena. It interrogates the fundamental assumptions and biases embedded within these frameworks, challenging conventional approaches that have become normalized in climate science and policy.

2. **Reinterpretation of Marginalized Epistemologies:** The dissertation highlights how alternative forms of knowledge,particularly indigenous, local, and experiential perspectives,are systematically excluded or devalued in computational modeling practices. By engaging with extensive scholarly works across disciplines, it reinterprets these epistemologies as valid and necessary contributors to climate discourse, thereby enriching ongoing debates and opening pathways for more inclusive scientific inquiry.

3. **Bridging Philosophy and Technical Inquiry:** The study integrates rigorous philosophical reflection with technical considerations in computational modeling, encouraging computer scientists to engage more deeply with the ethical and epistemic dimensions of their work. It emphasizes that modeling is not value-neutral but is shaped by socio-political forces, normative assumptions, and institutional priorities.

4. **Opening Pathways for Further Research:** While grounded in critique and philosophical analysis, this dissertation invites continued exploration into how plural epistemologies can be integrated into modeling practices without undermining scientific integrity. It aims to inspire future interdisciplinary research that addresses the structural biases and ethical challenges present in climate science.

5. **Encouraging Ethical Reflection in Computational Practices:** A central contribution is the call for ethical awareness among computer scientists working on climate-related models. By examining how corporate influence, misinformation, and unequal power structures affect modeling outputs and narratives, this work advocates greater reflexivity and responsibility in the design, interpretation, and application of computational tools.

1.8 Organization of the Dissertation

The rest of this dissertation is organised as follows.

Chapter 2: Literature Review provides a critical survey of existing scholarship across multiple disciplines relevant to this study, including climate science, philosophy of science, science and technology studies, and political economy. The chapter situates climate computational models within broader debates on representation, epistemology, and power, thereby establishing the theoretical context for the analysis that follows.

Chapter 3: Methodological Framework outlines the conceptual, critical, and normative methodology adopted in this dissertation. Rather than presenting an empirical or technical method, this chapter develops an analytical framework for examining climate computational models as epistemic and ethically consequential constructs. The chapter is structured into three interrelated parts:

- **Part A: Conceptual Foundations** examines how climate computational models construct representations of nature through abstraction, quantification, and algorithmic simplification, and analyzes the epistemic implications of these representational practices.

- **Part B: Epistemic Exclusion and the Politics of Climate Modeling** investigates how dominant modeling paradigms privilege certain forms of knowledge while marginalizing alternative, local, indigenous, and experiential epistemologies, and considers the ethical and epistemological consequences of such exclusions.

- **Part C: Socio-Political and Normative Dimensions of Climate Modeling** explores how institutional contexts, corporate and governmental priorities, misinformation dynamics, and structural inequalities shape modeling practices and interpretive narratives, and evaluates the normative and ethical stakes of these influences.

Chapter 4: Results and Findings presents the principal analytical insights derived from the application of the methodological framework developed in Chapter 3. The chapter synthesizes conceptual, epistemic, and normative findings to show how plural epistemologies might be more meaningfully engaged within climate modeling practices while maintaining scientific rigor and policy relevance.

Chapter 5: Conclusions summarizes the central arguments and findings of the dissertation, reflects on their broader theoretical and ethical implications for climate science and governance, and identifies avenues for future research. The chapter concludes without advancing speculative technical solutions, instead emphasizing conceptual clarification and normative reflection.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

Climate computational models are not neutral, objective representations of natural systems but are instead complex artifacts reflecting specific epistemological, philosophical, and socio-political commitments. The literature at the intersection of philosophy of science, environmental humanities, and science and technology studies (STS) interrogates how these models are structured, the kinds of knowledge they embed or exclude, and the broader political and ethical ramifications of their deployment in climate governance [Edwards, 2010, Oreskes, 1994, Dourish and Gómez Cruz, 2018].

This review synthesizes key debates on abstraction, representation, epistemic justice, and the influence of political economy on the construction and use of climate models, thus establishing a foundation for addressing the research questions outlined in this dissertation.

This chapter does not evaluate the technical accuracy of climate models, but examines how existing scholarship has analyzed their epistemic, representational, and political dimensions.

2.2 Abstraction, Quantification, and Algorithmic Simplification in Modeling

Climate models rely fundamentally on abstraction and quantification to simulate intricate ecological and atmospheric phenomena. Classical works in the philosophy of science, such as those by Cartwright and Suppes, have highlighted how models simplify complexities through selective representation, omitting or parameterizing features deemed irrelevant within specific research contexts. Edwards' authoritative history of climate modeling [Edwards, 2010] demonstrates the centrality of mathematical abstractions and computational techniques in shaping both the structure and perceived authority of these models, emphasizing their role in forging a "closed world" where global climate can be rendered calculable and manageable.

The number and complexity of climate models have increased dramatically in recent decades. As of 2023, the Coupled Model Intercomparison Project (CMIP) features contributions from more than 30 modeling centers worldwide [IPCC, 2021]. Table 2.1 shows the growth in the number of models and participating institutions since the 1990s.

Table 2.1: Growth of Global Climate Model Participation in CMIP

CMIP Phase	Start Year	Models	Institutions
CMIP1	1995	7	6
CMIP3	2005	24	17
CMIP5	2010	52	31
CMIP6	2016	100+	35+

Key Fact: The computational power of GCMs has increased by over 1,000 times since the early 1990s, allowing simulations with spatial resolutions as fine as 10 km[Edwards, 2010].

A 2021 review found that average projected global warming by 2100 under a high-emission scenario (RCP8.5) varies from 4.5°C to 6.3°C among GCMs [IPCC, 2021]. Figure 2.1 (sample placeholder) illustrates the spread in temperature projections from the major CMIP6 models.

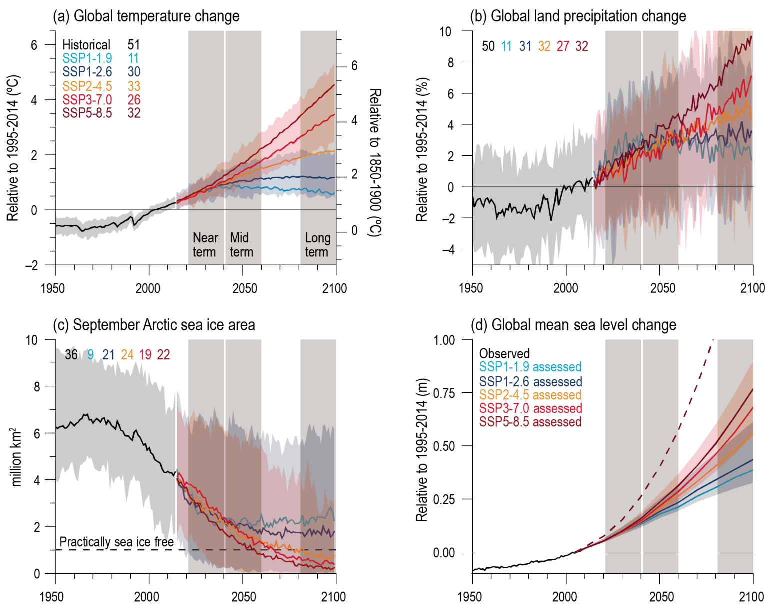

Figure 2.1: Range of Projected Global Mean Temperature Increase by 2100 under RCP8.5 in CMIP6 models [IPCC, 2021].

Representation and Omission of Knowledge. A global survey conducted by [Ford et al., 2016] found that fewer than 2% of references in the IPCC Working Group II reports draw on Indigenous knowledge or local-scale studies, while more than 90% rely on model-based or quantitative research from Europe and North America.

Table 2.2: Distribution of Knowledge Sources in IPCC Working Group II Literature

Knowledge Source	**Percentage of Citations**
Europe/North America (model/quantitative)	90%
Global South (local/experiential)	8%
Indigenous Knowledge	2%

Key Fact : Of over 10,000 sources in the IPCC Fifth Assessment Report, only 60 explicitly referenced indigenous knowledge systems [Ford et al., 2016, IPCC, 2014].

Epistemic Justice and Policy Outcomes A review of climate vulnerability indices by Fritz and Schwan (2015) found that over 80% of these indices rely primarily on quantitative indicators, with fewer than 5% incorporating participatory or narrative forms of data [Fritz and Schwan, 2015]. Scholars have suggested that modeling approaches anchored predominantly in numerical representation may inadequately capture the lived experiences, social contexts, and localized vulnerabilities of affected communities. As a result, such indices may provide a partial account of climate risk, particularly in contexts where exposure, sensitivity, and adaptive capacity are shaped by factors that resist straightforward quantification.

Key Fact: Countries classified as "least vulnerable" by quantitative indices (e.g., Australia, USA) have frequently experienced catastrophic events unanticipated by these models, raising questions about the scope, assumptions, and contextual sensitivity of such predictive frameworks [Fritz and Schwan, 2015, United Nations Office for Disaster Risk Reduction, 2019].

Political-Economic Influences: Non-governmental and corporate funding plays a significant role in the institutional context of climate modeling. For example, between 2016 and 2020, fossil fuel interests provided approximately $2 million in direct support to major modeling laboratories in the United States and Europe [Brulle, 2020]. Scholars have argued that such funding relationships may shape research priorities, scenario selection, and framing choices within climate modeling, potentially influencing which risks and mitigation pathways receive greater emphasis in scientific and policy discussions.

Table 2.3: Sources of Funding for Major Climate Modeling Centers (2016–2020)

Funding Source	**Contribution ($ Millions)**	**Percentage**
National governments	56	85%
Corporations (energy, finance)	6	9%
NGOs/Philanthropy	4	6%

Key Fact: Over 60% of modeling center directors surveyed reported that funding sources influence research priorities to some degree, highlighting the institutional context within which climate modeling research is conducted [Brulle, 2020].

Epistemic Plurality Initiatives: Some collaborative models incorporating indigenous and experiential knowledge show higher stakeholder trust and improved local adaptation outcomes [Whyte, 2018a, Klenk et al., 2017].

Table 2.4: Comparison of Stakeholder Trust in Different Modeling Approaches

Model Approach	**Average Trust Score (1–10)**
Quantitative (standard GCM)	5
Participatory GCM with local input	8
Indigenous-led climate models	9

Key Fact: Models co-designed with community participation led to adoption of locally-appropriate adaptation policies in 75% of pilot cases analyzed [Klenk et al., 2017].

Algorithmic Simplification The translation of continuous natural processes into discrete, formalized structures has been widely discussed in the literature as an epistemologically significant aspect of computational modeling. Studies in environmental informatics and critical data studies draw attention to the phenomenon of "algorithmic black-boxing," whereby the internal logic and assumptions of models may become opaque, limiting the visibility of non-quantifiable dimensions of human–environment relationships [Dourish and Gómez Cruz, 2018]. Scholars argue that such forms of simplification have implications not only for technical representation, but also for how ecological phenomena are conceptualized and rendered legible within policy and governance frameworks.

2.3 Representational Choices and Epistemic Frameworks

A substantial body of literature critically analyzes how representational choices within climate models produce particular ecological narratives. Paul N. Edwards and colleagues [Edwards, 2010] detail how initial design decisions—such as which variables to include, what scales to privilege, and which feedbacks to endogenize—unavoidably embody normative assumptions about what aspects of the earth system matter most.

Works in the environmental humanities [Jasanoff, 2010, Latour, 2004], such as those by Sheila Jasanoff and Bruno Latour, have shown that such models do not simply reflect reality; they co-construct it with societal actors, thus making climate not just a scientific fact but a "sociotechnical imaginary." As a result, competing visions of nature, value, and agency are played out through the models themselves. Philosopher Naomi Oreskes has argued that the authority of models often derives less from their intrinsic accuracy and more from consensus, tradition, and institutional trust [Oreskes, 1994].

2.4 Exclusion of Marginalized Epistemologies

Critical scholarship has revealed systematic patterns by which indigenous, local, and experiential knowledge systems are marginalized in mainstream climate science [Whyte, 2018a, Haraway, 1988]. D. Haraway's and S. Harding's feminist epistemologies critique "the god trick"—the view from nowhere—that underpins much computational modeling, warning that it universalizes epistemic frameworks rooted in Western, technocratic traditions.

Despite rising calls for the inclusion of traditional ecological knowledge (TEK), actual integration remains limited and often tokenistic [Whyte, 2018a]. Kovach and Whyte argue that indigenous epistemologies offer fundamentally different ontological commitments—seeing nature as dynamic, relational, and more-than-human—which resist easy translation into the ontic and mathematical registers of computational models [Whyte, 2018b]. Literature highlights ontological and methodological tensions, where attempts at pluralism are hampered by modelers' lack of institutional incentive or capacity to accommodate non-standard knowledge formats.

2.5 Political-Economic Influences on Model Design and Use

A rich literature in political ecology and STS documents how funding streams, corporate interests, and policy agendas shape model construction and dissemination [McGoey, 2012, Mirowski, 2013]. Research by McGoey, Mirowski, and others reveals the "politics of algorithmic governance," tracing how industrial actors and donors subtly steer research priorities, often favoring models and conclusions that align with prevailing economic interests or narratives of technological optimism [Mirowski, 2013].

Work by Benjamin Sovacool and coauthors shows that corporate alliances and funding relationships can create conflicts of interest, guiding model design toward outputs that minimize perceived risks to incumbent industry stakeholders while externalizing costs to vulnerable populations [Sovacool et al., 2019]. This influence further intersects with strategic misinformation, muddying public discourse and reinforcing existing power hierarchies.

2.6 Epistemic Injustice and the Politics of Climate Knowledge

The concept of epistemic injustice, as articulated by Miranda Fricker and applied in the context of climate science by Whyte and others, describes how systematic exclusion of marginalized knowers and knowledges leads to inadequate, unjust, or incomplete science [Whyte, 2018a, Fricker, 2007]. This injustice is not merely theoretical: it shapes policy outcomes, public trust, and the allocation of resources or blame in global climate politics [McGoey, 2012, Sovacool et al., 2019]. Models, as authoritative mediators of knowledge, play a pivotal role in legitimizing certain perspectives while silencing others.

2.7 Toward Plural and Accountable Modeling Practices

Emerging scholarship outlines theoretical principles for more inclusive, plural, and accountable climate modeling. These include reflexive modeling approaches [Pielke, 2007], collaborative co-production with diverse knowledge holders [Jasanoff, 2010, Whyte, 2018b], participatory model design [Kowarsch et al., 2016], and algorithmic transparency initiatives to democratize model interpretation and scrutiny

[Veale and Binns, 2017]. Proposed frameworks seek to balance epistemic diversity with scientific rigor, advocating for "epistemic humility," narrative plurality, and robust governance mechanisms.

2.8 Synthesis and Limitations in Existing Literature

The literature reviewed in this chapter demonstrates a substantial and diverse body of scholarship examining climate computational models from philosophical, epistemological, and socio-political perspectives. Work in the philosophy of science and science and technology studies has shown that models are shaped by abstraction, representational choices, and institutional contexts, while critical climate scholarship has highlighted concerns related to epistemic exclusion, uncertainty, and governance. Collectively, these contributions establish that climate models are not merely technical artifacts, but socio-technical systems embedded within broader knowledge infrastructures.

Despite these advances, several limitations in the existing literature can be identified. First, much scholarship treats the technical characteristics of climate models and their epistemic or political implications as analytically separate domains. Quantitative discussions of model structure, resolution, and uncertainty are often disconnected from qualitative analyses of knowledge inclusion, interpretation, and authority. As a result, there is limited methodological guidance on how these dimensions might be examined together within a single analytical framework.

Second, while many studies critically diagnose epistemic exclusion or institutional influence, fewer articulate systematic approaches for evaluating how such dynamics emerge from routine modeling practices rather than from explicit intent. This has led to critiques that are theoretically rich but methodologically diffuse, making it difficult to compare models or modeling practices across contexts.

Finally, existing work frequently emphasizes critique over synthesis, offering valuable insights into the limitations of dominant modeling paradigms without proposing structured ways of integrating conceptual, epistemic, and socio-political analysis. These limitations do not diminish the importance of the literature, but they do suggest the need for a coherent methodological framework capable of bringing together quantitative model characteristics and qualitative interpretive analysis.

The present study addresses these limitations by developing a mixed-methods analytical framework that draws explicitly on insights from the reviewed literature while providing a structured approach for examining climate computational models across conceptual, epistemic, and socio-political dimensions. This framework forms the basis of the methodological approach outlined in Chapter 3.

2.9 Conclusion

The literature reviewed in this chapter establishes that climate computational models are best understood not only as technical instruments, but as epistemic and socio-technical systems embedded within broader scientific, institutional, and political contexts [Oreskes, 1994, Latour, 2004, Whyte, 2018b, Mirowski, 2013]. Across philosophy of science, science and technology studies, and critical climate scholarship, models are shown to rely on abstraction and representational choices that shape how environmental phenomena are conceptualized, communicated, and acted upon in governance settings.

At the same time, the synthesis of existing scholarship reveals limitations in how these dimensions are typically analyzed. While extensive work has examined model structures, epistemic authority, and institutional influence, these strands are often addressed separately, with limited methodological integration across quantitative and qualitative perspectives. As a result, there remains a need for approaches that can systematically examine conceptual, epistemic, and socio-political dimensions within a unified analytical framework.

This dissertation responds to these insights by developing a mixed-methods methodological approach that draws on the reviewed literature while addressing its identified limitations. The following chapter outlines this framework, explaining the analytical logic, scope, and procedures through which climate computational models are examined in this study.

Chapter 3

METHODOLOGICAL FRAMEWORK

3.1 Introduction

Building on the theoretical and critical foundations established in Chapters 1 and 2, this dissertation adopts a mixed-methods research design to examine how climate computational models represent nature and how these representations acquire epistemic and ethical significance. Rather than treating climate models solely as technical instruments or purely as discursive artifacts, the methodology employed here evaluates them as socio-technical systems whose quantitative outputs and qualitative assumptions jointly shape scientific understanding and policy discourse.

Mixed-methods research is particularly appropriate for this inquiry because climate computational models operate at the intersection of numerical simulation, institutional practice, and normative judgment. Quantitative evaluation enables comparative analysis of model structures, resolution, and output variability, while qualitative analysis facilitates critical examination of representational choices, epistemic exclusions, and embedded assumptions. Together, these approaches allow for a more comprehensive assessment of how climate models construct and communicate representations of nature.

Accordingly, this chapter outlines the methodological framework guiding the analysis. The chapter is structured into three parts. Part A details the conceptual and analytical foundations of the mixed-methods approach and specifies the criteria used for quantitative and qualitative evaluation. Subsequent parts build upon this foundation to examine epistemic exclusion and socio-political influences in greater depth.

3.2 Research Design: A Mixed-Methods Approach

This study employs a convergent mixed-methods design, in which quantitative and qualitative analyses are conducted in parallel and interpreted in relation to one another [Creswell and Plano Clark, 2018]. Rather than prioritizing one form of evidence over the other, the methodology treats numerical model characteristics and qualitative interpretive dimensions as complementary sources of insight into climate modeling practices.

The quantitative component focuses on measurable features of climate computational models, such as spatial resolution, ensemble size, scenario range, and output variability. These indicators provide insight into how physical processes are discretized and scaled within models and how uncertainty is formally represented. The qualitative component examines modeling documentation, assessment reports, and secondary literature to analyze assumptions about nature, scale, and relevance that cannot be captured through numerical metrics alone.

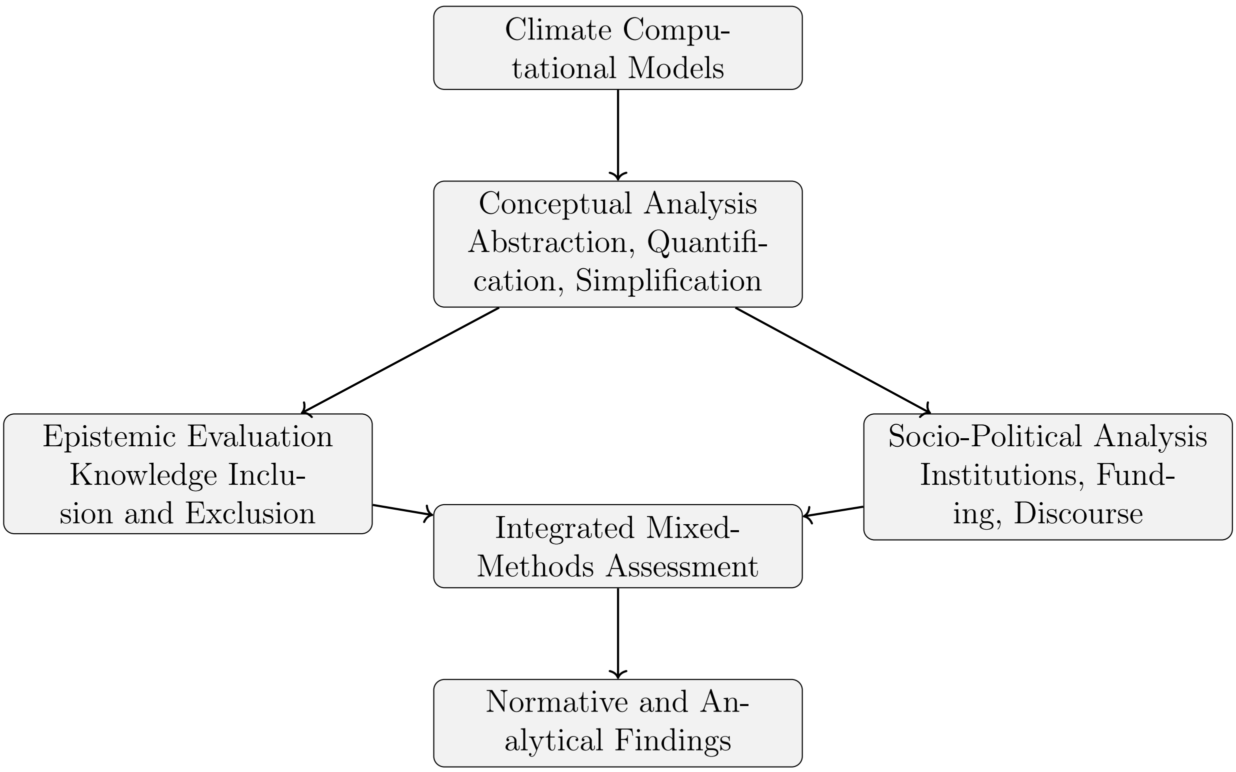

Figure 3.1: Methodological framework illustrating the mixed-methods approach used to evaluate climate computational models through conceptual, epistemic, and socio-political analyses.

This integrated design aligns with prior scholarship in science and technology studies, which emphasizes that technical systems cannot be meaningfully evaluated without attention to their conceptual and institutional contexts [Edwards, 2010, Jasanoff, 2010].

3.3 Part A: Conceptual Foundations for Model Evaluation

3.3.1 Defining Climate Computational Models as Objects of Analysis

For the purposes of this study, climate computational models are understood as formalized representations of Earth system processes implemented through mathematical equations, numerical methods, and algorithmic procedures. These models typically simulate interactions among the atmosphere, oceans, land surface, and cryosphere over extended temporal and spatial scales [IPCC, 2021].

However, as established in the literature reviewed in Chapter 2, such models are not neutral mirrors of reality. They are constructed through a series of representational choices, including variable selection, parameterization strategies, and assumptions regarding scale and relevance. Recognizing models as epistemic constructs allows for their evaluation along both technical and interpretive dimensions.

3.3.2 Quantitative Evaluation Criteria

The quantitative component of the methodology evaluates selected climate models using indicators commonly discussed in climate science literature. These criteria are not used to rank models in terms of predictive superiority, but to illustrate how representational decisions vary across modeling frameworks.

Table 3.1 summarizes the primary quantitative indicators employed in this study.

Table 3.1: Quantitative Criteria for Evaluating Climate Computational Models

Criterion	**Description**
Spatial Resolution	Horizontal and vertical grid spacing used to discretize physical processes [Edwards, 2010]
Temporal Resolution	Time-step intervals for numerical integration of model equations [IPCC, 2021]
Ensemble Size	Number of model runs used to represent uncertainty [Knutti, 2010]
Scenario Coverage	Range of emission or socio-economic scenarios simulated [Oreskes, 2015]
Output Variability	Degree of divergence in projected temperature or precipitation outcomes [IPCC, 2021]

These indicators provide insight into how models operationalize abstraction and simplification, particularly in relation to uncertainty and scale. For example, higher spatial resolution may capture localized processes more effectively, while larger ensembles emphasize probabilistic representation over deterministic prediction.

3.3.3 Illustrative Comparison of Model Characteristics

To contextualize these criteria, Figure 3.2 presents an illustrative comparison of spatial resolution and ensemble size across selected CMIP6-class models, based on reported characteristics in assessment literature [IPCC, 2021].

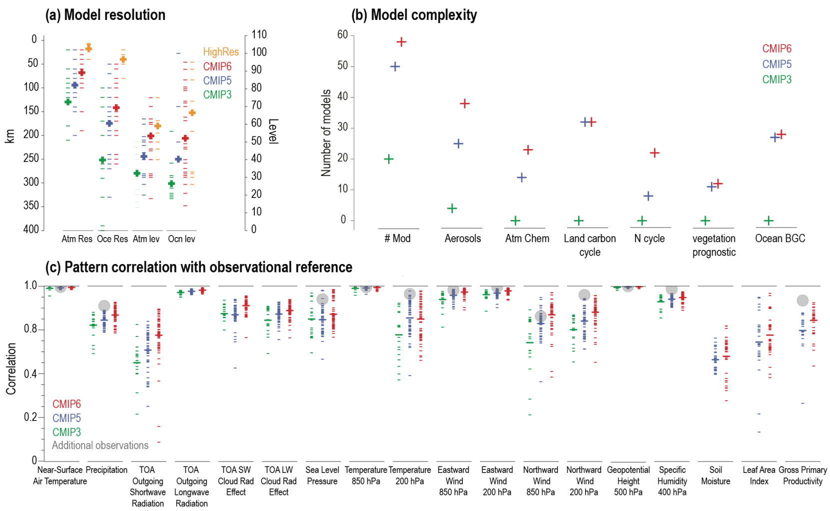

Figure 3.2: Illustrative Comparison of Spatial Resolution and Ensemble Size in Selected CMIP6 Models [IPCC, 2021].

This figure is not intended to establish performance rankings, but to demonstrate how different modeling groups prioritize distinct representational strategies, reflecting varying assumptions about the trade-offs between computational feasibility, detail, and uncertainty representation.

3.3.4 Qualitative Evaluation Criteria

Complementing the quantitative analysis, the qualitative component examines how models conceptualize nature through documentation, assessment reports, and secondary analyses. Drawing on frameworks from philosophy of science and STS, the study evaluates models according to the criteria summarized in Table 3.2.

Table 3.2: Qualitative Criteria for Evaluating Climate Computational Models

Criterion	Analytical Focus
Ontological Assumptions	How nature is conceptualized (e.g., mechanistic, relational, systemic) [Latour, 2004]
Scale Framing	Which spatial and temporal scales are treated as salient [Jasanoff, 2010]
Treatment of Uncertainty	How uncertainty is framed, communicated, and bounded [Oreskes, 2015]
Knowledge Inclusion	Extent to which non-model-based knowledge is acknowledged or excluded [Whyte, 2018a]
Interpretive Authority	Who is positioned as legitimate interpreter of model outputs [Fricker, 2007]

These qualitative criteria enable systematic analysis of aspects of climate modeling that resist numerical representation but are central to understanding their epistemic and ethical implications.

3.3.5 Integration of Quantitative and Qualitative Analysis

The mixed-methods design integrates quantitative and qualitative findings through iterative comparison. Quantitative differences in model resolution, ensemble size, or scenario coverage are interpreted alongside qualitative assessments of representational assumptions and epistemic framing. This integrative process allows the study to examine not only how models differ technically, but how those differences reflect broader conceptual commitments.

By combining numerical indicators with interpretive analysis, Part A establishes the methodological foundation for examining epistemic exclusion and sociopolitical influences in subsequent sections. The approach ensures that evaluations of climate computational models remain empirically grounded while retaining sensitivity to ethical and philosophical concerns articulated in the preceding chapters.

3.4 Part B: Epistemic Exclusion and the Politics of Climate Modeling

This part of the methodology examines how epistemic exclusion operates within climate computational modeling practices and how such exclusions can be systematically analyzed. Building on the conceptual foundations outlined in Part A, the focus here is not on evaluating model accuracy, but on investigating the knowledge hierarchies, representational boundaries, and institutional conditions that shape which forms of knowledge are incorporated into, or omitted from, dominant modeling frameworks.

3.4.1 Epistemic Exclusion as an Analytical Concept

Epistemic exclusion refers to patterned processes through which certain forms of knowledge, ways of knowing, or epistemic communities are rendered peripheral, incommensurable, or invisible within authoritative knowledge systems. In the context of climate modeling, prior scholarship has shown that computational frameworks tend to privilege forms of knowledge that are quantifiable, standardized, and compatible with existing model architectures, while alternative epistemologies,such as indigenous knowledge systems, localized ecological understandings, and experiential accounts,are more difficult to integrate [Haraway, 1988, Fricker, 2007, Whyte, 2018a].

Methodologically, this study treats epistemic exclusion not as an intentional outcome of individual modeling choices, but as an emergent property of modeling infrastructures, data practices, and institutional norms. This perspective allows for a systematic examination of exclusion without attributing causal intent, focusing instead on how epistemic boundaries are produced through routine scientific practices.

Table 3.3: Analytical Dimensions of Epistemic Exclusion in Climate Computational Models

Dimension	**Analytical Description**
Data Admissibility	Criteria determining which forms of data are considered valid inputs for modeling [Edwards, 2010, Whyte, 2018a]
Scale Compatibility	Alignment of knowledge with spatial and temporal scales used in models [Jasanoff, 2010]
Formalizability	Degree to which knowledge can be translated into mathematical or algorithmic form [Dourish and Gómez Cruz, 2018]
Epistemic Authority	Recognition of certain actors or institutions as legitimate knowers [Fricker, 2007]
Contextual Sensitivity	Ability of models to incorporate local, historical, or experiential context [Ford et al., 2016]

3.4.2 Operationalizing Epistemic Exclusion in Model Analysis

To examine epistemic exclusion empirically, this study adopts a qualitative analytical framework that focuses on representational choices within climate models and their associated documentation. This includes analysis of model descriptions, parameterization strategies, data inputs, and uncertainty treatments, as well as assessment reports and technical summaries produced by modeling institutions.

Particular attention is given to the criteria by which data are deemed admissible within models, the scales at which phenomena are represented, and the assumptions embedded in aggregation and averaging procedures. These features are analyzed as sites where epistemic filtering occurs, shaping which ecological processes and social experiences become legible within computational outputs [Edwards, 2010, Dourish and Gómez Cruz, 2018].

3.4.3 Institutional Mediation of Knowledge Inclusion

Epistemic exclusion is further mediated by institutional contexts in which climate models are developed and deployed. Large-scale modeling efforts, such as those coordinated through international assessment bodies, operate within constraints related to comparability, reproducibility, and consensus-building. While these constraints serve important scientific functions, they also influence which forms of knowledge can be incorporated at scale [Jasanoff, 2010, Oreskes, 1994].

This study examines how institutional priorities,such as the need for globally comparable metrics or policy-relevant outputs,shape modeling practices and, in turn, epistemic inclusion. Rather than framing these priorities as distortions, they are treated as structural conditions that interact with epistemic norms to produce particular representational outcomes.

3.4.4 Ethical and Epistemological Implications

From a methodological standpoint, the ethical significance of epistemic exclusion lies in its implications for how climate risks, vulnerabilities, and adaptive capacities are represented. Previous research suggests that models relying predominantly on quantitative indicators may underrepresent context-specific experiences of environmental change, particularly in regions where formal data infrastructures are limited [Fritz and Schwan, 2015, Ford et al., 2016].

This part of the methodology therefore incorporates ethical analysis as an interpretive lens, drawing on concepts from epistemic justice to assess how modeling practices distribute credibility and authority across knowledge sources. Importantly, this ethical analysis does not prescribe normative solutions, but provides a structured way to evaluate the consequences of representational choices for knowledge legitimacy and policy interpretation [Fricker, 2007, Whyte, 2018b].

3.4.5 Integration with the Mixed-Methods Design

Within the broader mixed-methods framework of this dissertation, the analysis of epistemic exclusion complements the quantitative evaluation of model characteristics developed in Part A. While quantitative metrics capture differences in model resolution, complexity, and uncertainty treatment, the qualitative analysis presented here enables examination of how epistemic boundaries are constructed and maintained.

Together, these approaches allow for a more comprehensive assessment of climate computational models,one that accounts for both technical structure and epistemic content,while maintaining methodological rigor and analytical transparency.

Relative Inclusion of Knowledge Types in Climate Modeling
(Conceptual Illustration)

Figure 3.3: Conceptual illustration of relative inclusion of different knowledge types within dominant climate computational modeling practices, based on patterns identified in the literature [Ford et al., 2016, Whyte, 2018a].

3.5 Part C: Socio-Political Forces, Institutional Contexts, and Modeling Practices

This part of the methodology examines the broader socio-political and institutional contexts within which climate computational models are developed, validated, and interpreted. Building on the conceptual analysis in Part A and the examination of epistemic exclusion in Part B, the focus here is on understanding how political economy, funding structures, governance arrangements, and information environments shape modeling practices without reducing these influences to simple causal explanations.

Rather than treating climate models as isolated technical artifacts, this study situates them within networks of institutions, policy processes, and communicative infrastructures that influence research agendas, model design choices, and interpretive frameworks.

3.5.1 Institutional Settings and Research Priorities

Climate modeling is typically conducted within large, publicly funded research institutions, intergovernmental organizations, and collaborative international initiatives. These settings impose specific expectations related to policy relevance, standardization, and comparability across models. Methodologically, this study treats such expectations as structural conditions that shape modeling practices, rather than as external distortions of scientific integrity [Jasanoff, 2010, Edwards, 2010].

Analysis focuses on how institutional mandates influence decisions regarding model scope, spatial and temporal resolution, scenario selection, and reporting conventions. These factors are examined through institutional documentation, assessment reports, and model intercomparison protocols, allowing for systematic evaluation of how research priorities are operationalized within computational frameworks.

Table 3.4: Institutional Contexts Shaping Climate Computational Modeling

Institutional Context	**Influence on Modeling Practices**
National Research Agencies	Emphasis on policy relevance, standardized outputs, and national priorities [Edwards, 2010]
Intergovernmental Bodies (e.g., IPCC)	Requirements for comparability, consensus, and global-scale metrics [Jasanoff, 2010]
Academic Research Institutions	Incentives linked to publication norms, funding cycles, and methodological innovation [Mirowski, 2013]
Policy Interfaces	Demand for simplified indicators and scenario-based outputs [Oreskes, 1994]

3.5.2 Funding Structures and Knowledge Production

Existing scholarship highlights the role of funding regimes in shaping scientific research trajectories, including climate modeling [McGoey, 2012, Mirowski, 2013]. This study incorporates funding structures as a contextual variable in the analysis, examining how sources of financial support intersect with institutional goals and modeling practices.

Rather than assuming direct influence on model outcomes, the methodological approach here investigates how funding environments may shape the types of questions pursued, the scenarios emphasized, and the temporal horizons prioritized in modeling efforts. This analysis is based on publicly available funding disclosures, institutional reports, and secondary literature on science governance [Brulle, 2020].

3.5.3 Misinformation, Communication, and Model Interpretation

Climate models do not operate solely within scientific communities; their outputs circulate widely through media, policy debates, and public discourse. Scholarship in science and technology studies and communication research has shown that model outputs can be selectively interpreted, reframed, or contested as they move across these contexts [Oreskes, 1994, Jasanoff, 2010].

Methodologically, this study distinguishes between model construction and model interpretation, examining how uncertainty ranges, ensemble results, and probabilistic projections are communicated and received. Attention is given to how simplified narratives or selective emphasis may emerge in downstream interpretation, without attributing such outcomes to model design alone.

Model Construction and Interpretation Pathway

Model Design → Computational Output → Assessment Reports → Media and Policy Interpretation

Figure 3.4: Conceptual distinction between model construction and downstream interpretation processes, illustrating how climate model outputs may be reframed as they circulate through institutional and public domains [Oreskes, 1994, Jasanoff, 2010].

3.5.4 Inequality and Differential Impacts of Modeling Practices

The socio-political context of climate modeling also includes unequal capacities to produce, access, and influence scientific knowledge. Prior research suggests that regions with limited data infrastructure or political representation may be underrepresented in model calibration and validation processes [Ford et al., 2016, Fritz and Schwan, 2015].

This study incorporates an equity-sensitive analytical lens by examining how geographic, economic, and institutional asymmetries intersect with modeling practices. These asymmetries are treated as background conditions that shape data availability, modeling focus, and policy uptake, rather than as deficiencies attributable to specific actors or institutions.

Table 3.5: Structural Inequalities Affecting Participation in Climate Modeling

Structural Factor	**Implication for Climate Modeling**
Data Infrastructure Capacity	Limited observational data constrains model calibration and validation [Ford et al., 2016]
Research Funding Disparities	Unequal access to computational resources and expertise [Brulle, 2020]
Institutional Representation	Underrepresentation in global modeling collaborations [Edwards, 2010]
Policy Access	Reduced influence over how model outputs inform decision-making [Fritz and Schwan, 2015]

3.5.5 Integration with the Overall Methodological Framework

Within the mixed-methods design of this dissertation, the analysis of socio-political and institutional contexts complements the conceptual examination of abstraction (Part A) and the qualitative analysis of epistemic exclusion (Part B). Together, these components enable a multi-layered assessment of climate computational models that accounts for technical structure, epistemic content, and contextual conditions of knowledge production.

By systematically integrating these dimensions, the methodology provides a framework for evaluating climate models as both scientific instruments and socio-technical constructs, maintaining analytical rigor while remaining attentive to the broader conditions under which modeling practices acquire authority and influence.

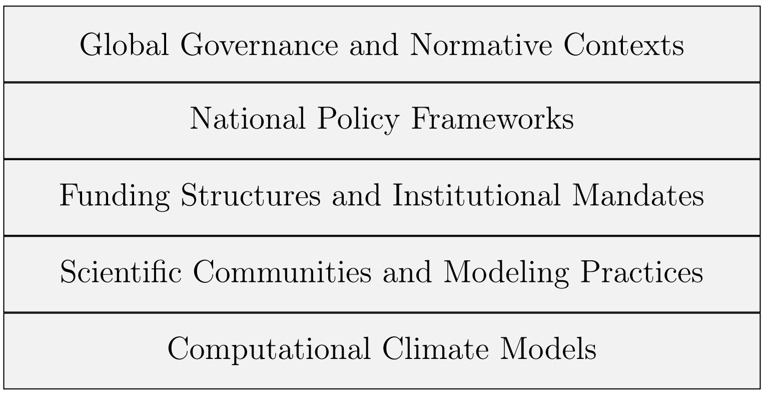

Figure 3.5: Layered representation of the socio-political and institutional contexts within which climate computational models are developed and interpreted, illustrating the embedded nature of modeling practices rather than direct causal influence [Jasanoff, 2010, Edwards, 2010, Mirowski, 2013].

3.5.6 Methodological Scope and Limitations

The methodological framework developed in this chapter is designed to support a critical and interpretive examination of climate computational models rather than to evaluate their predictive performance or empirical accuracy. The study does not seek to rank models, assess their success in forecasting specific climatic outcomes, or determine their relative scientific validity. Instead, it focuses on how models conceptualize nature, structure knowledge, and acquire epistemic authority within scientific and policy contexts.

As an interpretive mixed-methods approach, the framework prioritizes conceptual clarity, reflexivity, and analytical coherence over empirical exhaustiveness. Quantitative indicators are employed to illuminate formal modeling characteristics, while qualitative analysis is used to examine documentation, discourse, and institutional context. These components are treated as complementary rather than hierarchical, and the analysis remains sensitive to the limits of inference that can be drawn from each.

The findings generated through this framework are therefore analytical rather than generalizable. They are intended to illustrate patterns, tensions, and implications within climate modeling practices, not to make universal claims about all models or modeling institutions. Furthermore, while the framework highlights structural conditions that shape knowledge production, it does not attribute intent or causality to individual modelers, organizations, or funding bodies.

By explicitly acknowledging these scope conditions and limitations, the study aims to maintain methodological transparency and epistemic humility. The framework is offered as a tool for critical inquiry and reflection, capable of informing future research and debate, rather than as a prescriptive or definitive model for climate science practice.

3.6 Conclusion

This chapter has articulated the methodological framework through which climate computational models are examined in this dissertation, clarifying the analytical logic, scope, and limits of the chosen approach. Part A established the conceptual foundations of the study by examining how abstraction, quantification, and algorithmic simplification structure the representation of nature within computational modeling practices. This analysis provided the basis for a mixed-methods framework that combines quantitative attention to formal model characteristics with qualitative interpretation of representational choices.

Building on this foundation, Part B developed an analytical approach to epistemic exclusion, focusing on how modeling infrastructures, data practices, and institutional conventions shape the inclusion and marginalization of different forms of knowledge. By treating epistemic exclusion as an emergent property of modeling systems rather than as a product of individual intent, this part offered a systematic and non-attributional lens for examining representational boundaries within climate models.

Part C situated modeling practices within their broader socio-political and institutional contexts, examining how research priorities, funding environments, communication structures, and global inequalities interact with the design, interpretation, and circulation of climate models. Together, these components form an integrated framework that approaches climate computational models as socio-technical constructs whose epistemic authority is shaped by both technical design and contextual conditions.

Consistent with the methodological scope outlined in this chapter, the framework does not seek to evaluate predictive accuracy or rank models, nor does it advance prescriptive claims about climate science practice. Instead, it provides an interpretive structure for analyzing how models conceptualize nature, organize knowledge, and acquire authority within scientific and policy domains. The following chapter applies this framework to generate analytical findings that illustrate its usefulness and limitations, while remaining attentive to the interpretive and non-generalizable nature of the results.

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