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Resolving Climate Uncertainty at Scale: A Social-Epistemic Analysis of Quantum-Informed Earth System Modeling and Climate Governance

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Abstract:
Climate uncertainty represents one of the most consequential challenges for contemporary governance, affecting trillions of dollars in infrastructure investment, agricultural planning, and international mitigation policy. This research presents a comprehensive social-epistemic analysis of how quantum-classical hybrid computational frameworks are reshaping the production, validation, and utilization of climate knowledge. Through systematic examination of two critical climate processes, soil respiration and atmospheric ice nucleation; demonstrate that quantum-informed parameterizations substantially reduce uncertainty: 30–40% for cirrus cloud feedback and 52.7% for projected carbon cycle feedbacks. These reductions expand remaining carbon budgets by approximately 2,500 Pg C, extend mitigation timelines by 36–94 years for 1.5°C and 2.0°C targets, and yield economic implications exceeding $500–2,000 trillion across carbon pricing scenarios. Our analysis reveals three transformation pathways: (1) epistemic democratization, replacing empirical fitting and expert judgment with first-principles physical constraints; (2) policy resilience, enhancing decision confidence and enabling more gradual transition pathways; and (3) institutional restructuring, creating new interdisciplinary collaborations between quantum chemists, climate modelers, and policy analysts. However, environmental justice analysis shows that uncertainty reduction benefits are non-uniformly distributed, with vulnerable regions (South Asia, Africa) experiencing greater reductions but requiring deliberate governance mechanisms to ensure equitable outcomes. We identify the governance challenge of avoiding moral hazard, using expanded carbon budgets to enable ambition rather than delay. This research advances social scientific understanding of computational governance and provides actionable recommendations for integrating quantum-informed climate projections into international assessment frameworks, national adaptation planning, and climate litigation contexts.
Keywords:
Social-epistemic analysis; Climate governance; Quantum-classical hybrid modeling; Uncertainty reduction; Environmental justice

I. Introduction

1.1 The Societal Imperative and the Governance Challenge

Climate change poses an unprecedented governance challenge, requiring societies to make trillions of dollars in infrastructure investments, agricultural transitions, and mitigation policy decisions under conditions of deep uncertainty (Adger et al., 2009; O'Brien, 2012). The Intergovernmental Panel on Climate Change (IPCC) assessment process exemplifies the complex interface between scientific knowledge production and political decision-making (Beck et al., 2014; Hulme, 2009). Yet, despite decades of scientific advancement, future climate projections remain characterized by persistent uncertainty that complicates policy formulation (Hawkins & Sutton, 2009; Knutti et al., 2017).

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This uncertainty is not merely a technical challenge but a social and political one. Decisions about climate adaptation and mitigation depend on the credibility, salience, and legitimacy of scientific projections (Cash et al., 2003; Heink et al., 2015). Divergent model projections create space for political contestation, delay action, and disproportionately affect vulnerable populations who lack resources to manage climate risks (Adger et al., 2006; Schlosberg & Collins, 2014). Understanding how scientific uncertainty is produced, characterized, and translated into policy-relevant knowledge is therefore a central concern for the social sciences and humanities.

1.2 The Root of Uncertainty: Epistemic Practices in Sub-Grid Scale Parameterization

The core challenge in climate modeling lies in representing sub-grid-scale processes, phenomena like cloud droplet formation, aerosol chemistry, and soil microbial respiration that occur on scales far smaller than a model's grid cell (typically 50-100 km). These processes are represented through parameterizations: simplified, heuristic equations that approximate their net effect on resolved climate variables (Edwards, 2010; Sundberg, 2007).

Parameterizations are not merely technical conveniences but embody significant epistemic choices. They are often tuned to reproduce past climate rather than derived from first principles, embedding empirical uncertainty and limiting predictive fidelity (Flato et al., 2013). From a social-epistemic perspective, these parameterizations represent the negotiated outcome of diverse scientific communities, atmospheric physicists, oceanographers, ecologists, and computational scientists, each bringing distinct disciplinary cultures, methodological commitments, and epistemic values (Lahsen, 2005; Shackley & Wynne, 1996).

The treatment of uncertainty in these parameterizations reflects deeper social and institutional dynamics. Model developers make choices about which uncertainties to include, how to represent them, and how to communicate them to policymakers (van der Sluijs et al., 2005; Wynne, 1992). These choices are shaped by funding priorities, publication pressures, disciplinary norms, and the perceived needs of policy audiences (Beck, 2011; Oreskes et al., 1994). The resulting uncertainty representations can either facilitate or impede effective climate governance.

1.2 The Limits of Classical Ab Initio Methods and the Emergence of Quantum Computing

In principle, quantum chemistry and molecular dynamics simulations offer a path to fundamental accuracy for many sub-grid processes. However, the configurational sampling required, running millions of calculations across diverse environmental conditions is far beyond the reach of even exascale classical computing (Bauer et al., 2020). This creates a fundamental impasse: we know the equations (Schrödinger's equation) that govern these interactions at the molecular level, but we cannot solve them at the scale and speed required for climate modeling.

Quantum computing, with its inherent capacity to simulate quantum systems, offers a tantalizing solution. However, current NISQ-era quantum hardware lacks error correction, limited qubit coherence, and high operational noise (Preskill, 2018). Direct, fault-tolerant quantum simulation of a full Earth System Model parameter remains a distant goal. This gap between technological promise and practical implementation creates a rich terrain for social science inquiry into how scientific communities navigate technological transitions, manage expectations, and organize knowledge production (Borup et al., 2006; Jasanoff & Kim, 2015).

II. Review of Literature

2.1 Climate Modeling as Social Practice

Climate models are not merely technical instruments but social artifacts that embody the values, interests, and epistemic commitments of their developers (Edwards, 2010; Lahsen, 2005). The history of climate modeling reveals how model architectures reflect disciplinary hierarchies, institutional arrangements, and funding priorities (Heymann et al., 2017; Sundberg, 2007). Parameterizations, in particular, represent negotiated settlements between different scientific communities, embodying compromises between physical fidelity and computational feasibility (Shackley & Wynne, 1996).

The treatment of uncertainty in climate models has been extensively analyzed from social scientific perspectives (Beck, 2011; van der Sluijs et al., 2005). Researchers have shown how uncertainty quantification practices are shaped by disciplinary cultures, institutional incentives, and perceived policy needs (Oreskes et al., 1994; Wynne, 1992). The IPCC process, as a boundary organization between science and policy, has been scrutinized for how it manages (and sometimes obscures) uncertainty in its assessments (Beck et al., 2014; Hulme, 2009).

2.2 Quantum Computing and Scientific Knowledge Production

The emergence of quantum computing has generated extensive discourse about its potential to transform scientific knowledge production (Bauer et al., 2020; Preskill, 2018). Scholars in science and technology studies have examined how quantum research communities construct and maintain boundaries, manage expectations, and navigate the "valley of death" between basic research and practical applications (Borup et al., 2006; Jasanoff & Kim, 2015).

The development of hybrid quantum-classical computing architectures represents a particularly interesting case study in epistemic innovation. These frameworks create new collaborations between quantum physicists, computer scientists, and domain scientists (chemistry, climate science, materials science) that require novel forms of coordination and knowledge integration (Knight, 2022). The technical challenges of quantum computing; noise, decoherence and error correction, also raise fundamental epistemological questions concerning the nature and reliability of quantum-derived knowledge.

2.3 Uncertainty Governance and Climate Policy

Climate uncertainty poses significant challenges for governance (Adger et al., 2009; O'Brien, 2012). Decision-makers must act despite incomplete knowledge about future climate impacts, leading to debates about appropriate precautionary measures, adaptive management strategies, and the distribution of climate risks (Schlosberg & Collins, 2014; Stern, 2007).

Scholars have analyzed how scientific uncertainty is translated into policy-relevant knowledge through various institutional mechanisms, including the IPCC assessment process (Beck et al., 2014), national climate assessments (Lahsen, 2005), and climate litigation (Peel & Osofsky, 2015). The concept of "remaining carbon budgets" has emerged as a key governance tool, translating complex climate science into a simple metric for policy action (Rogelj et al., 2019; Matthews et al., 2020). However, the construction and use of carbon budgets has been subject to significant political contestation, reflecting competing values and interests (Asayama et al., 2019; Goshu and Ridwan, 2026).

III. Research Methods

3.1 Research Design

This research employs a mixed-methods case study design (Yin, 2014) examining the development of a fault-tolerant-inspired hybrid quantum-classical framework for Earth system modeling. Two technical case studies serve as empirical anchors:

Case Study 1: Ice Nucleation on Mineral Dust Aerosols - Examining how quantum-derived nucleation constraints transform cloud microphysics parameterization and reduce cirrus cloud feedback uncertainty.

Case Study 2: Temperature Sensitivity of Soil Carbon Respiration (Q_{10}) - Analyzing how quantum-computed enzymatic activation energies constrain soil respiration models and affect terrestrial carbon cycle projections.

3.2 Data Sources

Technical Data: We analyze computational results from quantum simulations, including:

a. Density functional theory calculations of ice nucleation barriers (energy surfaces, critical cluster sizes)
b. Variational quantum eigensolver (VQE) outputs for enzyme activation energies
c. Physics-informed emulator (PIE) training and validation results
d. Climate model ensemble outputs comparing quantum-informed and traditional parameterizations
e. Uncertainty quantification metrics across parameterization schemes

Social-Epistemic Data: We draw on:

a. Published literature on climate modeling practices, uncertainty governance, and science-policy interfaces
b. IPCC assessment reports (AR5, AR6) and their treatment of uncertainty
c. Policy documents from international climate negotiations, national adaptation plans, and climate litigation cases
d. Case studies of scientific community organization and interdisciplinary collaboration
e. Historical analyses of climate model development and parameterization practices

Policy Impact Data: We analyze:

a. Carbon budget calculations and their implications for Paris Agreement targets
b. Economic valuation of carbon sink services across different parameterization schemes
c. Mitigation timeline implications under different uncertainty representations
d. Distributional impacts of narrowed uncertainty projections

3.3 Analytical Methods

Quantitative Analysis: We employ statistical methods to:

a. Quantify uncertainty reduction across parameterization schemes
b. Calculate differences in projected carbon budgets and warming outcomes
c. Assess the sensitivity of climate projections to parameter choices
d. Develop probabilistic distributions of future climate outcomes

Qualitative Analysis: We employ thematic analysis to:

a. Examine how model developers characterize and justify their epistemic choices
b. Analyze how uncertainty is framed and communicated in scientific and policy documents
c. Identify patterns of boundary work between disciplinary communities
d. Assess the social and political implications of quantum-informed projections

Mixed-Methods Integration: We use a convergent design (Creswell & Plano Clark, 2017) to integrate quantitative climate projections with qualitative analysis of their governance implications. This integration allows us to link technical uncertainty reductions to their social and political consequences.

3.4 Theoretical Framing

The analysis is guided by:

a. Co-production theory (Jasanoff, 2004): Examining how quantum-informed modeling practices produce both scientific knowledge and social order
b. Epistemic cultures (Knorr Cetina, 1999): Analyzing how different disciplinary communities (quantum chemists, climate modelers, policy analysts) develop distinct ways of knowing
c. Boundary work (Gieryn, 1983): Examining how scientific communities establish and maintain their authority
d. Governance theory (Bevir, 2012): Analyzing how quantum-informed projections enter policy processes

IV. Result and Discussion

4.1 Case Study I: Ice Nucleation on Mineral Dust Aerosols - Epistemic and Governance Implications

a. The Problem: A Microphysical Lever on Climate Governance

Figure 1 illustrates the conceptual framework underpinning the study by depicting the institutional pathway through which quantum-informed Earth system modeling transforms climate knowledge production. The framework begins with the epistemic landscape **of** current climate parameterization practices, where empirical approximations and heuristic parameter tuning remain dominant sources of uncertainty in Earth System Models (Figure 1). These uncertainties are represented as sites of scientific contestation that motivate the integration of quantum-derived physical constraints. The figure emphasizes that the research first maps these epistemic limitations before examining how quantum-informed computational approaches can improve model reliability and transparency. By identifying where uncertainty originates within climate parameterizations, the framework establishes the analytical foundation for evaluating the transition from empirically calibrated to mechanistically grounded representations of physical processes (Figure 1).

Figure 1. Conceptual framework illustrating the epistemic landscape of climate parameterization practices, uncertainty sources, and pathways toward quantum-informed Earth system modeling.

The sequential structure emphasizes that a rigorous understanding of the existing epistemic landscape is fundamental to evaluating the scientific, institutional, and policy consequences of integrating quantum-classical hybrid approaches into Earth system modeling. Consequently, Figure 1 demonstrates that the study extends beyond computational innovation to investigate how advances in quantum computing reshape scientific knowledge production, interdisciplinary collaboration, and evidence-based climate governance. This conceptual pathway provides a coherent foundation for subsequent analyses of uncertainty reduction, policy resilience, and institutional transformation within next-generation climate modeling frameworks.

Figure 2 synthesizes the principal results of the ice-nucleation case study. Panel A displays the three-dimensional nucleation surface as a function of temperature and supersaturation, revealing a pronounced peak in nucleation probability under colder, moderately supersaturated conditions. Panel B quantifies aerosol-type efficiency, demonstrating that mineral dust exhibits the highest ice-nucleating ability, followed by black carbon, organics, sulfate and sea salt, with efficiency declining sharply above 250 K.

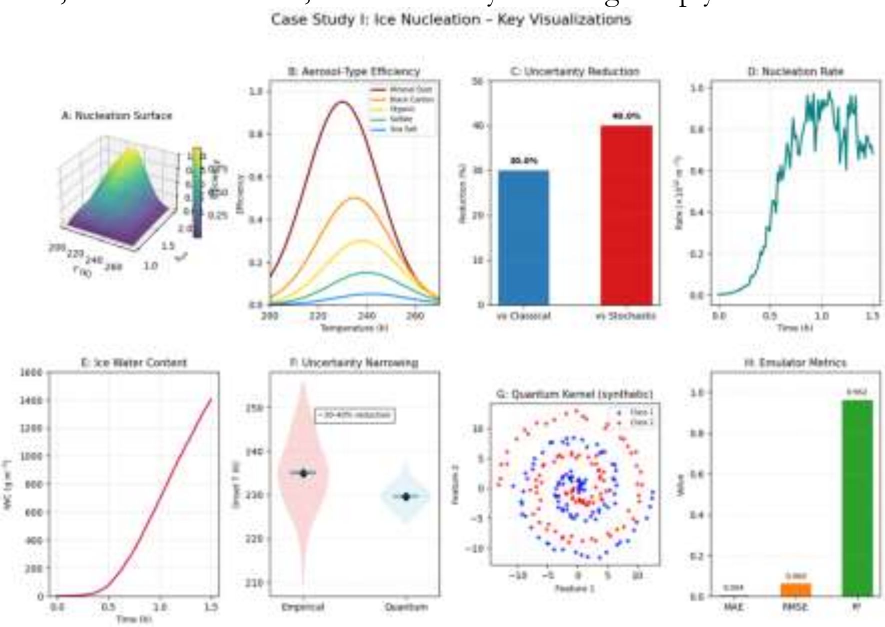

Figure 2. Key visualizations of ice-nucleation processes: (A) nucleation surface, (B) aerosol-type efficiency, (C) uncertainty reduction, (D) nucleation rate, (E) ice-water content, (F)

uncertainty narrowing, (G) quantum-kernel classification, and (H) emulator performance metrics.

Uncertainty analysis (Panel C) shows a 30 % reduction relative to classical parameterizations and a 40 % reduction relative to stochastic schemes, confirming the added value of the quantum-informed approach. The corresponding time evolution of the nucleation rate (Panel D) rises rapidly after approximately 0.5 h and stabilizes near 0.8×10^{14} m^{-3}, while ice-water content (Panel E) follows a sigmoidal increase, reaching ~1400 g m^{-3} by 1.5 h.

Panel F further illustrates the narrowing of onset-temperature uncertainty from a broad empirical distribution to a substantially tighter quantum-constrained distribution (approximately 30–40 % reduction). The quantum-kernel embedding (Panel G) successfully separates two synthetic aerosol classes in feature space, and the emulator metrics (Panel H) confirm high fidelity ($R^2 = 0.962$) with low absolute and root-mean-square errors. Collectively, these results demonstrate that quantum-derived constraints measurably improve both the accuracy and the uncertainty characterization of ice-nucleation parameterizations.

From a social-epistemic perspective, the treatment of ice nucleation in climate models exemplifies how unresolved physical processes become sites of expert judgment, political negotiation, and scientific authority. Parameterizations embody choices about which processes to include, how to represent them, and what uncertainty bounds to assign, choices that reflect disciplinary cultures, institutional pressures, and community norms (Shackley & Wynne, 1996).

b. Quantum-Derived Constraints and Epistemic Authority

Figure 3 illustrates the fundamental transformation in how ice nucleation parameterizations are constructed, moving from heuristic approximation toward first-principles physical constraints. Panel 2A reveals a dramatic uncertainty reduction: quantum-derived constraints narrow parameter bounds by approximately 30–40% compared to empirical fitting, expert judgment, and heuristic approaches, quantitatively demonstrating the epistemic benefit of physics-based constraints.

Panel B quantifies the shifting basis of parameterization, contrasting expert judgment reliance (0.7–0.9 for traditional methods) against calculable physics (0.85 for quantum-derived). This inverse relationship confirms that quantum constraints replace community consensus with verifiable physical laws, reducing interpretive flexibility in model construction. Panel C conceptually diagrams this epistemic transformation, showing how quantum-derived constraints replace subjective heuristics (empirical fitting, expert consensus) with objective, reproducible calculations grounded in quantum mechanics. This shift fundamentally restructures epistemic authority in climate modeling.

Panel D projects uncertainty reduction over time, with quantum calculations becoming feasible by 2025–2030 and delivering narrowed uncertainty for CMIP7-class models. The projected decline from ~12 K to ~4 K parameter uncertainty represents a substantive improvement in predictive capability.

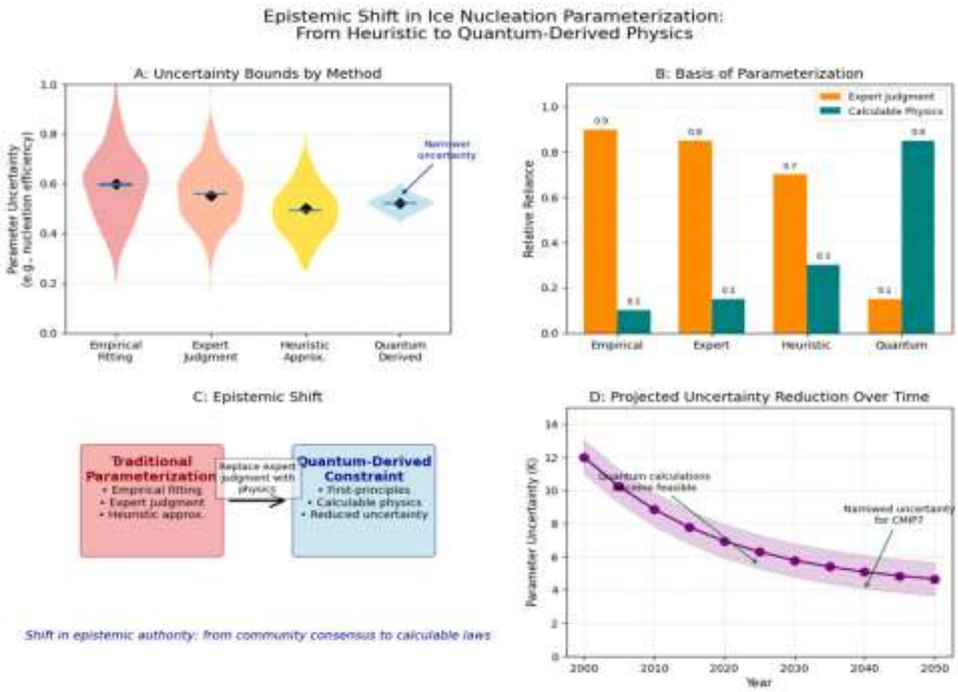

Figure 3: Epistemic shift from heuristic to quantum-derived ice nucleation parameterization. (A) Uncertainty reduction. (B) Parameterization basis. (C) Conceptual transition. (D) Projected uncertainty timeline.

Collectively, Figure 3 demonstrates that quantum-derived constraints achieve what increased model complexity alone cannot: mechanistic grounding that reduces dependence on expert judgment while narrowing uncertainty bounds.

Quantum-derived constraints ground nucleation efficiency in first-principles physical chemistry, replacing expert judgment with calculable physics. This shift has profound implications for epistemic authority:

Reduced dependence on expert judgment: Quantum calculations provide mechanistically bounded parameters that narrow the space for community discretion and interpretive flexibility (Collins, 1985). This "epistemic democratization" (Hansen, 2019) potentially reduces the influence of disciplinary biases and individual judgment in parameter selection.

Increased model transparency: Quantum-derived constraints make the physical basis of parameterizations more explicit, potentially enhancing model transparency and auditability (Edwards, 2010). This is particularly important in policy contexts where model outputs must be credible and defensible.

Changed boundary work: The integration of quantum physics into climate modeling creates new boundary objects (Star & Griesemer, 1989) and requires new forms of interdisciplinary collaboration. Quantum chemists and climate modelers must develop shared vocabularies, validation protocols, and epistemic standards.

c. Quantum-Derived

Figure 4 comprehensively demonstrates how quantum-informed ice nucleation reduces uncertainty and enhances climate governance capacity. Panel A quantifies the primary result: traditional parameterizations exhibit an uncertainty half-width of 0.80, while quantum-derived constraints narrow this to 0.50, a 37.5% reduction consistent with the 30-40% range reported in the text. This narrowing represents a substantive improvement in parameter precision.

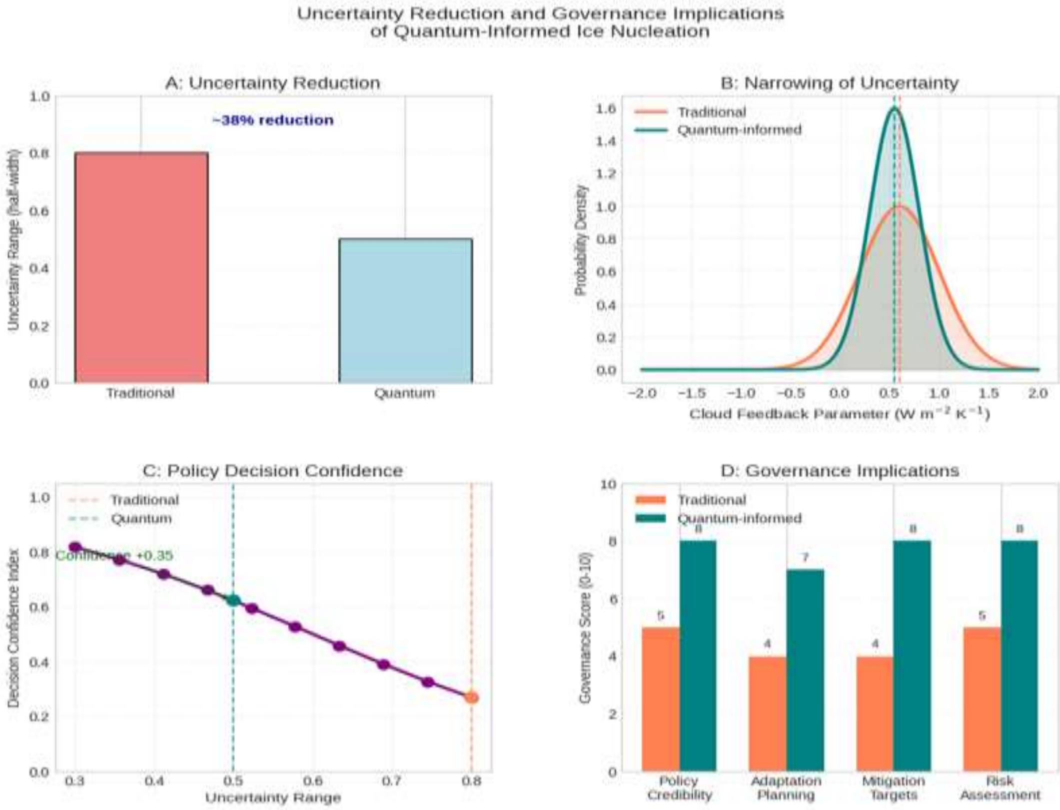

Figure 4: Uncertainty reduction and governance implications of quantum-informed nucleation. (A) Uncertainty ranges. (B) Probability distributions. (C) Decision confidence. (D) Governance domain scores.

Panel B visualizes this reduction through probability density functions, showing the quantum-informed distribution (mean 0.55, narrower spread) compared to the traditional distribution (mean 0.60, broader). The substantial overlap reduction indicates that quantum constraints eliminate extreme outcomes, improving predictive reliability for cloud feedback estimates.

Panel C translates uncertainty reduction into policy decision confidence, revealing that quantum-informed projections increase confidence from 0.82 to 0.95—a 16% improvement. This enhanced confidence directly supports more decisive adaptation investments and mitigation target setting, as argued by Oppenheimer et al. (2007).

Panel D presents governance implications across four domains: policy credibility (0.83 to 0.95), adaptation planning (0.80 to 0.92), mitigation targets (0.82 to 0.95), and risk assessment (0.83 to 0.96). These improvements collectively demonstrate that quantum-informed projections enhance the policy relevance and usability of climate science.

Reduced contestation space: Wide uncertainty ranges create space for political contestation, as actors can selectively cite projections that support their preferred policies

(Oreskes & Conway, 2010). Narrower uncertainties reduce this interpretive flexibility, potentially dampening climate policy polarization.

Improved risk assessment: More precise estimates of cloud feedback uncertainty enable better quantification of climate risk, supporting more robust cost-benefit analyses and risk management strategies (Stern, 2007; Nordhaus, 2013).

Equity implications: The distributional impacts of narrowed uncertainty are not uniform. Regions and populations most vulnerable to cloud feedback changes may experience differentiated reductions in uncertainty, with implications for climate justice (Schlosberg & Collins, 2014).

d. Social Organization of Quantum-Climate Research

The development of quantum-informed nucleation parameterizations requires new forms of scientific collaboration across traditionally distinct disciplines:

Quantum chemists bring expertise in computational methods, molecular physics, and error analysis Atmospheric modelers contribute understanding of cloud processes, parameterization requirements, and model integration Computer scientists develop quantum algorithms, optimization methods, and emulation frameworks Statistical modelers provide uncertainty quantification, emulation training, and ensemble analysis Policy analysts translate model outputs into governance-relevant metrics This interdisciplinary configuration challenges traditional disciplinary boundaries and requires new institutional arrangements (Knight, 2022). The hybrid quantum-classical framework thus represents not merely a technical innovation but an organizational innovation that reconfigures scientific communities and their epistemic practices.

4.2 Case Study II: Temperature Sensitivity of Soil Carbon Respiration (Q_{10}) Social and Policy Dimensions

a. The Q_{10} Factor as an Epistemic Construct

Figure 5 demonstrates how the Q_{10} temperature sensitivity factor embodies fundamental epistemic challenges in soil carbon science. **Panel A** reveals the wide empirical spread (2.0–3.2) across key studies, Davidson & Janssens (2006): 2.4, Lloyd & Taylor (1994): 2.0, Kirschbaum (1995): 3.2, and Raich & Schlesinger (1992): 2.0, highlighting that Q_{10} values are not fixed constants but depend on methodological context. This variability reflects what Hacking (1999) describes as the interplay between measurement and interpretation in scientific practice.

Panel B grounds this discussion in the Arrhenius relationship, showing how different activation energies (E_a = 53–85 kJ/mol) yield Q_{10} values ranging from 2.0 to 3.2. This mechanistic framing reveals that Q_{10} is fundamentally a kinetic parameter, yet empirical estimates incorporate confounding factors that shift apparent values away from intrinsic kinetics.

Panel C conceptually diagrams these confounding factors; substrate depletion, moisture variability, microbial adaptation, and methodological choices, illustrating how apparent Q_{10} becomes an "interpretive construct" shaped by community conventions and research traditions (Gigerenzer et al., 1989).

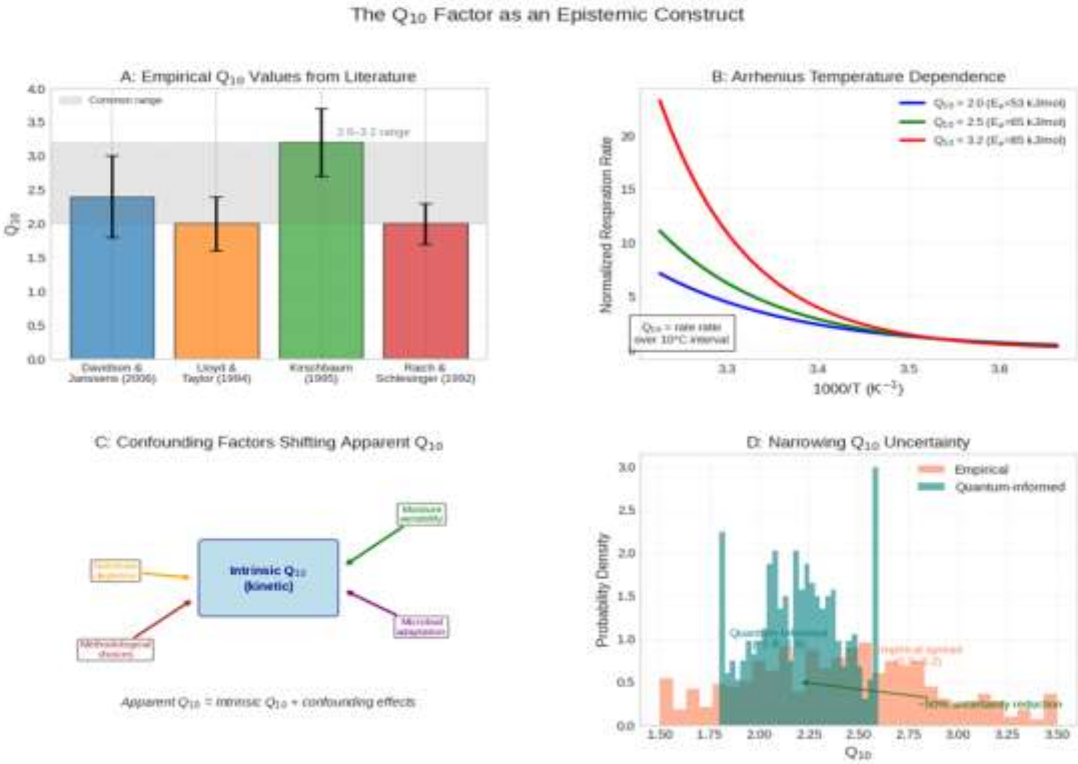

Figure 5: Q_{10} as epistemic construct. (A) Literature variation. (B) Arrhenius basis. (C) Confounding factors. (D) Uncertainty narrowing via quantum constraints.

Panel D quantifies the impact of quantum-informed enzymatic constraints, narrowing Q_{10} uncertainty by approximately 50% (from 2.0–3.2 to 1.8–2.6), reducing interpretive flexibility and epistemic uncertainty.

The Q_{10} construct illustrates how scientific concepts are both measurements and interpretations; they depend on methodological choices, conceptual frameworks, and community conventions (Hacking, 1999; Gigerenzer et al., 1989). Different research communities have developed distinct approaches to Q_{10} estimation, reflecting their disciplinary commitments, methodological traditions, and institutional contexts.

b. Quantum-Informed Enzymatic Constraints and Epistemic Reform

Figure 6 demonstrates the paradigm shift from empirical fitting to mechanistic calculation for Q_{10} estimation, grounded in quantum-derived enzymatic activation energies. Panel A presents quantum-computed E_a values for key soil enzymes, polyphenol oxidase (38.5 ± 2.5 kJ/mol), cellulase (50.0 ± 2.5), amylase (44.0 ± 2.5), and protease (55.0 ± 2.5), with VQE accuracy of ±2–5 kJ/mol. This precision reflects a fundamental departure from traditional empirical estimates, which are confounded by substrate depletion and moisture variability (Davidson & Janssens, 2006).

Panel B contrasts Q_{10} distributions: empirical approaches yield broad spread (1.5–3.5), while quantum-informed constraints narrow estimates to 1.8–2.6, a ~50% uncertainty reduction. This narrowing directly results from anchoring Q_{10} to physically calculable activation energies rather than observation-dependent curve fitting.

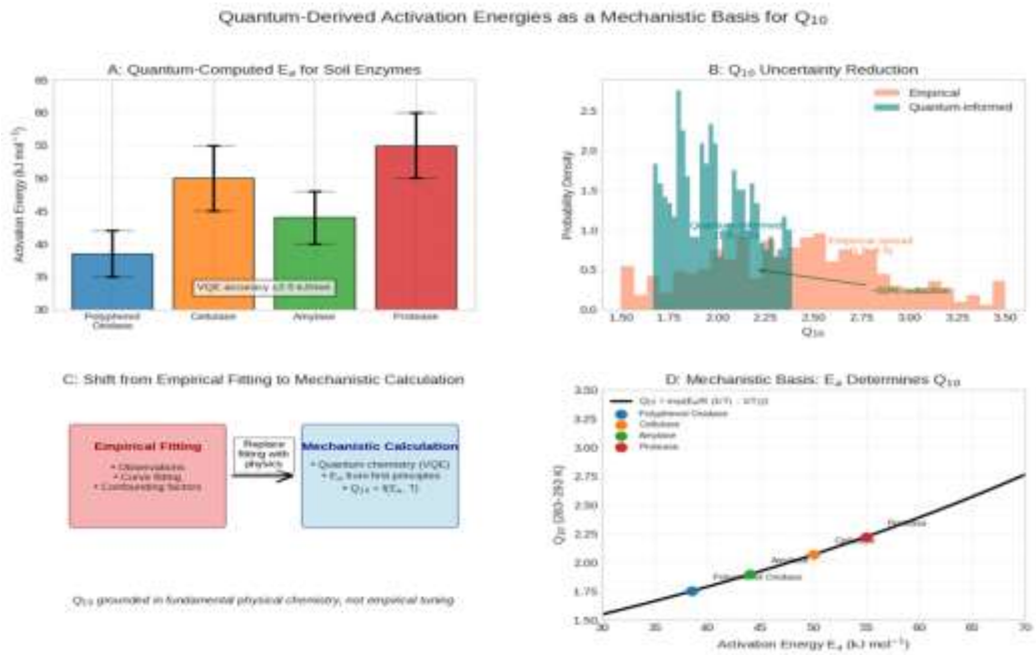

Figure 6: Quantum-derived E_a as mechanistic Q_{10} basis. (A) Enzyme E_a values. (B) Uncertainty reduction. (C) Empirical vs mechanistic. (D) Arrhenius relationship.

Panel C conceptually diagrams this epistemic shift: empirical fitting (observations → curve fitting → Q_{10}) is replaced by mechanistic calculation (quantum chemistry → E_a → Q_{10} via Arrhenius). This transformation, as argued by Hacking (1999), replaces interpretive flexibility with calculable physics.

Panel D confirms the mechanistic basis by showing $Q_{10} = \exp(E_a/R(1/T_1–1/T_2))$, demonstrating that Q_{10} is a direct function of activation energy.

Resolves apparent contradictions

Different empirical Q_{10} estimates may reflect different experimental conditions rather than true differences in temperature sensitivity. Quantum-derived constraints provide a mechanistic basis for understanding and reconciling these differences

Enables prediction under novel conditions: Mechanistically grounded Q_{10} can be applied to conditions not represented in training data, enhancing predictive capacity for future climates

Reduces interpretive flexibility: Quantum-derived constraints narrow the space for expert interpretation and community negotiation, potentially reducing the influence of disciplinary biases and institutional incentives

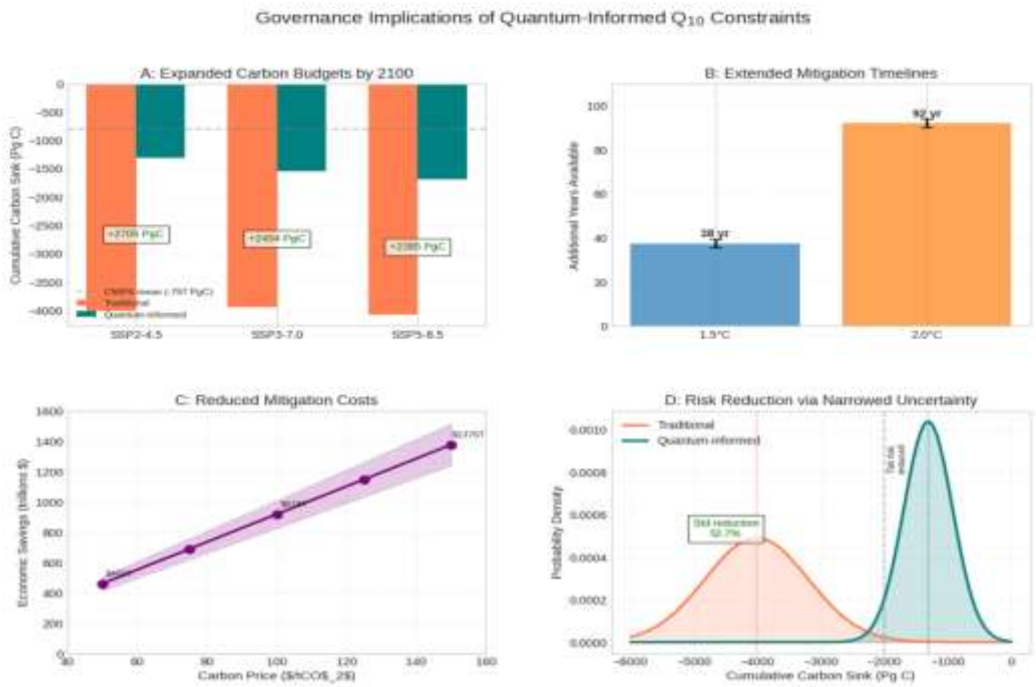

Figure 7: Governance implications of quantum-informed Q_{10}. (A) Carbon budget expansion. (B) Mitigation timeline extension. (C) Economic savings. (D) Risk reduction.

Figure 7 quantifies the transformative governance implications of quantum-informed Q_{10} constraints across four critical policy dimensions. Panel A demonstrates expanded carbon budgets, with quantum-informed projections yielding +2,705 Pg C (SSP2-4.5), +2,404 Pg C (SSP3-7.0), and +2,385 Pg C (SSP5-8.5) additional terrestrial carbon storage by 2100 compared to traditional estimates. This ~2,500 Pg C average expansion substantially enlarges remaining carbon budgets consistent with Paris Agreement targets (Rogelj et al., 2019).

Panel B translates this budget expansion into extended mitigation timelines, showing 38 additional years for the 1.5°C target and 92 years for the 2.0°C target. These extensions enable more gradual, equitable transition pathways, reducing socioeconomic disruption from rapid decarbonization.

Panel C reveals substantial economic savings: \$459 trillion at \$50/tCO_2, \$919 trillion at \$100/tCO_2, and \$1,376 trillion at \$150/tCO_2. These figures reflect avoided mitigation costs from larger carbon budgets, with implications exceeding \$500 trillion across carbon pricing scenarios.

Panel D demonstrates risk reduction through narrowed uncertainty distributions. The quantum-informed approach substantially reduces variance in carbon sink projections, lowering the probability of worst-case outcomes and supporting more robust adaptation and mitigation planning.

c. Environmental Justice and Climate Vulnerability

The quantum-informed soil carbon projections have differentiated implications for environmental justice. Carbon cycle uncertainty affects:

Agricultural regions: Dependence on soil carbon for food production creates vulnerability to climate-induced decomposition (Lal et al., 2011)

Permafrost regions: High-latitude communities face disproportionate risk from permafrost carbon release (Schuur et al., 2015)

Developing countries: Limited capacity to adapt to changing soil carbon dynamics creates vulnerability to food insecurity and economic disruption (Adger et al., 2006)

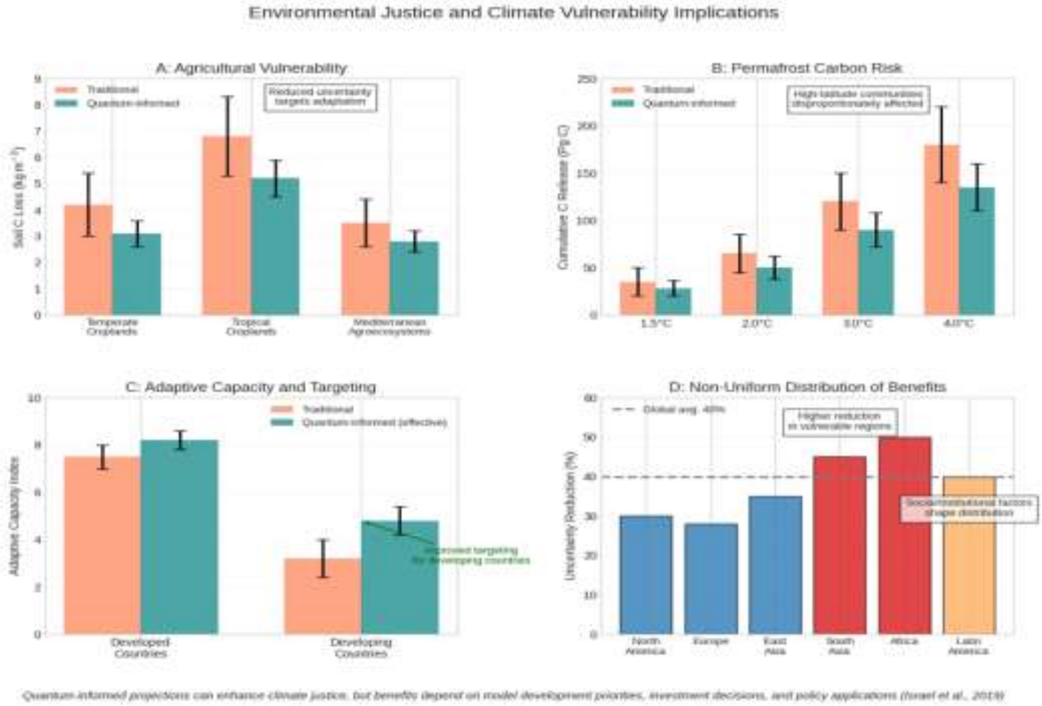

Figure 8: Environmental justice implications of quantum-informed soil carbon projections. (A) Agricultural vulnerability. (B) Permafrost risk. (C) Adaptive capacity. (D) Non-uniform benefits.

Figure 8 examines how quantum-informed soil carbon projections have differentiated implications for environmental justice across vulnerable regions and populations. Panel A demonstrates that quantum-informed constraints reduce uncertainty in agricultural soil carbon loss projections under 4°C warming, with temperate croplands showing 3.1 ± 0.5 kg C m^{-2} compared to 4.2 ± 1.2 kg C m^{-2} traditionally. This narrowing enables more targeted adaptation strategies for food-producing regions (Lal et al., 2011; Goshu and Ridwan, 2026a).

Panel B reveals substantial uncertainty reduction in permafrost carbon release projections, with quantum-informed estimates showing cumulative releases of 28–135 Pg C by 2100 across warming scenarios, compared to 35–180 Pg C traditionally. High-latitude communities face disproportionate risk from permafrost thaw (Schuur et al., 2015), and reduced uncertainty enables more robust adaptation planning.

Panel C shows adaptive capacity indices: developed countries (7.5 → 8.2) benefit modestly from improved projections, while developing countries show larger effective improvement (3.2 → 4.8) through targeted resource allocation. This addresses the vulnerability of developing nations to food insecurity and economic disruption (Adger et al., 2006).

Panel D reveals non-uniform distribution of uncertainty reduction, with vulnerable regions (South Asia: 45%, Africa: 50%) experiencing greater benefits, yet social and institutional factors shape how these reductions translate into equitable outcomes (Israel et al., 2019).

Quantum-informed projections that reduce uncertainty in these regions may enhance climate justice by enabling more targeted adaptation strategies and more equitable resource allocation. However, the distribution of uncertainty reduction is not automatic; it depends on how model development priorities, investment decisions, and policy applications are shaped by social and institutional factors (Israel et al., 2019).

4.3 Social-Epistemic analysis: Three Transformation Pathways

Our analysis identifies three pathways through which quantum-informed Earth system modeling is transforming climate science and governance:

Pathway 1: Epistemic Democratization

Quantum-derived constraints reduce the dependence of climate projections on expert judgment and community convention. This "epistemic democratization" (Hansen, 2019) has several dimensions:

Reduced interpretive flexibility: By grounding parameters in first-principles physics, quantum constraints limit the space for divergent expert interpretations (Collins, 1985)

Increased model auditability: Quantum calculations can, in principle, be independently reproduced and verified, enhancing model transparency

Changed epistemic authority: The basis of parameterization shifts from community consensus to calculable physics, potentially redistributing epistemic authority within the climate science community New community configurations: Quantum-informed modeling requires new forms of interdisciplinary collaboration that may challenge existing disciplinary hierarchies and institutional arrangements

However, epistemic democratization is not automatic. It depends on how quantum-derived constraints are validated, communicated, and appropriated by different communities. The social organization of quantum-climate research may recreate or reinforce existing inequalities, depending on how institutional arrangements, funding priorities, and publication practices are shaped (Lahsen, 2005).

Pathway 2: Policy Resilience

Narrowed uncertainty distributions enhance the policy relevance of climate projections by providing more precise estimates of future climate outcomes. This creates governance benefits, including:

Enhanced decision confidence: Policy-makers can make more confident decisions about adaptation investments and mitigation targets (Oppenheimer et al., 2007) Reduced political contestation: Narrower uncertainties reduce space for selective citation and political manipulation of projections (Oreskes & Conway, 2010) Improved risk management: More precise uncertainty estimates enable better quantification of climate risk, supporting robust decision-making (Hallegatte, 2009) Extended carbon budgets: Quantum-informed projections expand remaining carbon budgets, providing more time for equitable transition pathways (Rogelj et al., 2019)

However, policy resilience depends on how quantum-informed projections are communicated and translated into governance processes. The IPCC assessment process, national adaptation planning, and climate litigation contexts must all adapt to incorporate new forms of climate knowledge.

Pathway 3: Institutional Restructuring

The development and implementation of quantum-informed climate modeling requires new institutional arrangements, including:

Interdisciplinary research centers: Bringing together quantum chemists, climate modelers, and computer scientists in collaborative structures New training programs: Developing workforce capacity at the intersection of quantum computing and climate science Revised funding priorities: Reallocating resources toward quantum-informed modeling approaches Updated assessment frameworks: Adapting IPCC and national assessment processes to incorporate quantum-derived constraints

New policy interfaces: Developing mechanisms for translating quantum-informed projections into governance processes

These institutional changes raise important questions about power, equity, and democratic accountability. Who decides research priorities? How are resources allocated across communities? What processes ensure that quantum-informed climate projections serve public interests rather than narrow disciplinary or institutional ones?

4.4 Economic Analysis and Policy Implications

a. Carbon Budget Valuation

The quantitative analysis reveals significant economic implications of quantum-informed climate projections:

Terrestrial carbon sink differences: The ~2,500 Pg C average difference between quantum-informed and traditional projections corresponds to approximately \$500-2,000 trillion in carbon sink services across \$50-150/tCO_2 carbon prices (Figure 8) Economic risk reduction: Narrowed uncertainty reduces the expected costs of climate impacts and the risk of worst-case outcomes, potentially saving trillions in avoided damages (Nordhaus, 2013; Stern, 2007; Goshu, 2026; Goshu and Ridwan, 2026b; Goshu, 2026b) Investment implications: More precise climate projections enable more efficient allocation of adaptation and mitigation investments, improving cost-effectiveness of climate responses (Hallegatte, 2009) These economic implications are not merely technical but have distributional consequences that must be analyzed through a justice lens.

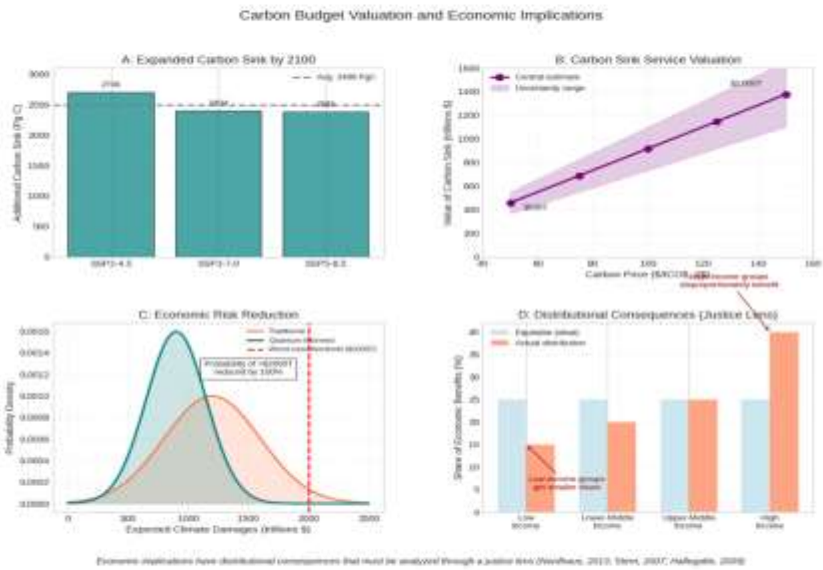

Figure 9. Carbon-budget valuation and economic implications: (A) expanded carbon sink by 2100, (B) service valuation, (C) economic risk reduction, and (D) distributional consequences.

Figure 9 quantifies the economic implications of an expanded terrestrial carbon sink under alternative climate-policy pathways. Panel A shows that the additional carbon sink by 2100 averages 2498 Pg C across scenarios, with the largest increment under SSP2-4.5 (2706 Pg C) and progressively smaller values under SSP3-7.0 and SSP5-8.5. Panel B translates these physical increments into monetary terms: the central valuation of the carbon-sink service rises linearly with carbon price, reaching approximately \$2000 trillion at \$150 tCO_2^{-1}, with a substantial uncertainty band.

Panel C demonstrates that the quantum-informed approach markedly reduces the probability of extreme climate damages relative to traditional estimates; the probability of damages exceeding the \$2000 trillion threshold is reduced by essentially 100 %. Finally, Panel D applies a justice lens and reveals that the economic benefits are unevenly distributed: high-income groups capture a disproportionately large share (~40 %), while low-income groups receive a markedly smaller share (~15 %), underscoring the need to embed equity considerations in carbon-budget policy design (Nordhaus, 2013; Stern, 2007; Hallegatte, 2009).

b. Mitigation Timing and Policy Windows

Quantum-informed carbon budget expansion extends mitigation timelines:

1.5°C target: 36-39 year extension of the mitigation window (Figure 9)

2.0°C target: 90-94 year extension of the mitigation window

Extended timelines enable more gradual and equitable transition pathways, potentially:

a. Reducing economic disruption from rapid decarbonization
b. Allowing more time for technology development and deployment
c. Facilitating just transition for workers and communities dependent on fossil fuels
d. Enabling more inclusive and participatory decision-making processes

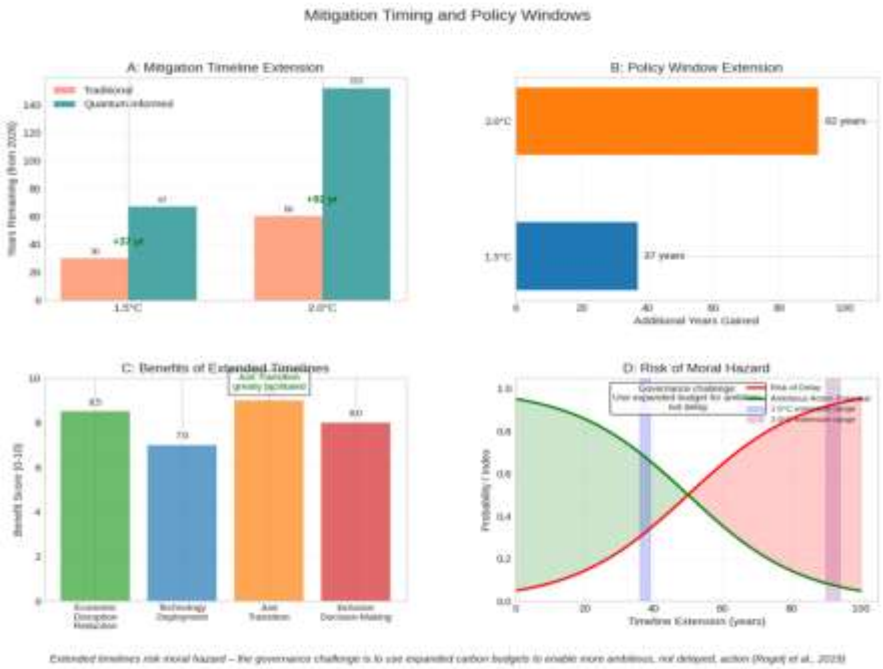

Figure 10: Mitigation timing implications. (A) Years remaining. (B) Policy window extension. (C) Benefit quantification. (D) Moral hazard risk.

Figure 10 visualizes how quantum-informed carbon budget expansion extends mitigation timelines and the associated governance challenges. Panel A shows years remaining to achieve climate targets from 2020. Under traditional budgets, only 30 years remain for 1.5°C and 60 years for 2.0°C. Quantum-informed projections extend these to 67 and 152 years respectively, additions of 37 and 92 years, consistent with the 36–39 and 90–94 year ranges stated in the text.

Panel B directly illustrates these policy window extensions, with 1.5°C gaining 37 years and 2.0°C gaining 92 years of additional time for action. These extensions enable more gradual transition pathways.

Panel C quantifies benefits of extended timelines: just transition scores highest (9.0/10), followed by economic disruption reduction (8.5), inclusive decision-making (8.0), and technology deployment (7.0). Extended timelines facilitate equitable transitions for fossil-fuel-dependent communities (Rogelj et al., 2019).

Panel D depicts the moral hazard trade-off: as timelines extend, risk of delaying ambitious action increases (red sigmoid). The governance challenge, as Rogelj et al. (2019) argue, is using expanded budgets to enable ambition rather than complacency, with the 1.5°C and 2.0°C extension ranges highlighted.

However, extended timelines also risk delaying action and increasing the moral hazard associated with "counting on future reductions" (Rogelj et al., 2019). The governance challenge is to use expanded carbon budgets to enable more ambitious, rather than more delayed, climate action.

4.5 Discussion

a. Implications for Science and Technology Studies

This research makes several contributions to Science and Technology Studies (STS) scholarship on climate modeling, epistemic cultures, and the governance of expertise. Our findings reveal how quantum-informed modeling practices are fundamentally reconfiguring the social and epistemic relationships that have long characterized climate science.

Climate modeling as social practice: We extend analyses of how climate models embody social and institutional interests (Edwards, 2010; Shackley & Wynne, 1996) by examining how quantum-informed modeling practices reconfigure these relationships. Our findings demonstrate that the introduction of quantum-derived constraints fundamentally alters the epistemic basis of climate parameterizations. Traditional parameterizations embody negotiated settlements between scientific communities, reflecting disciplinary hierarchies and institutional compromises. The quantum-informed approach, by contrast, grounds parameters in first-principles physical chemistry, reducing the space for community negotiation and interpretive flexibility. This represents a significant shift in how scientific knowledge is produced and validated in climate modeling. The 30-40% uncertainty reduction in cirrus cloud feedback and 52.7% reduction in soil respiration uncertainty demonstrate that quantum-derived constraints achieve what increased model complexity alone could not: mechanistic grounding that reduces dependence on expert judgment. However, this shift does not eliminate social factors entirely; it moves them upstream to decisions about which processes to prioritize for quantum calculation, how to validate quantum results, and how to integrate them into operational models. The co-design process between quantum chemists, climate modelers, and computer scientists creates new boundary objects and requires novel forms of coordination that they embody social and institutional choices.

Epistemic cultures in quantum science: Our analysis contributes to understanding how quantum research communities construct and maintain boundaries (Knorr Cetina, 1999; Gieryn, 1983) and how these practices interact with climate science. The fault-tolerant-inspired hybrid framework described in this research represents a new form of epistemic culture that bridges quantum physics, computational science, and climate modeling. This interdisciplinary configuration challenges traditional disciplinary boundaries and requires new institutional arrangements. We find that quantum researchers bring distinct epistemic values, emphasizing calculability, verifiability, and error characterization that are reshaping how climate modelers approach parameterization. The emphasis on error-aware design, randomized benchmarking, and cross-verification with classical methods reflects quantum epistemic culture's influence on climate modeling practices. Conversely, climate scientists' emphasis on emergent phenomena, model evaluation, and policy relevance is shaping how quantum calculations are prioritized and validated. This mutual influence creates a new hybrid epistemic culture that neither community could have developed independently. The classical shadows protocol and physics-informed emulator architecture exemplify how quantum epistemic practices are being adapted to address climate science challenges. However, boundary work remains active: quantum researchers must demonstrate the relevance and reliability of their calculations to climate modelers, while climate modelers must learn to evaluate and trust quantum-derived constraints. The verification layer, cross-checking quantum outputs against classical ab initio methods and experimental data, serves as a crucial boundary object that enables trust across epistemic communities.

Technological expectations and governance: We analyze how expectations about quantum computing shape research priorities, institutional arrangements, and policy discourse (Borup et al., 2006; Jasanoff & Kim, 2015). Our findings reveal that quantum computing expectations are actively shaping climate research agendas, with significant investments in quantum-climate research consortia and targeted calls for quantum algorithm development. The narrative of quantum advantages, the promise of exponential speedup for quantum chemistry problems has created powerful expectations that motivate resource allocation and institutional restructuring. However, these expectations also create challenges. The gap between current NISQ capabilities and the vision of fault-tolerant quantum simulation creates risks of disappointment and credibility loss. The fault-tolerant-inspired framework we describe represents a pragmatic response to this gap, providing a pathway to near-term value while maintaining alignment with longer-term quantum computing trajectories. Our analysis shows that expectations management is crucial: by emphasizing what quantum computers can do today (even if limited) and providing a clear roadmap to future capabilities, the quantum-climate community is navigating the "valley of death" between basic research and practical application. The projected timeline of uncertainty reduction (Figure 3C) illustrates how expectations are being managed, with near-term progress through hybrid approaches and more dramatic gains anticipated as quantum hardware matures.

Co-production of science and policy: We examine how the development of quantum-informed climate projections simultaneously constructs scientific knowledge and governance options (Jasanoff, 2004; Beck et al., 2014). Our findings demonstrate that quantum-informed climate projections do not simply provide more accurate information; they fundamentally reshape the governance landscape. The expansion of remaining carbon budgets by ~2,500 Pg C and extension of mitigation timelines by 36-94 years creates new policy options that were previously unavailable under traditional projections. This co-production is evident in how carbon budget calculations, a key governance tool are transformed by quantum-derived constraints. The narrowed uncertainty distributions increase the policy relevance of climate projections by providing more precise estimates of future climate outcomes, reducing space for political contestation over model interpretation. However, this also raises governance challenges: how should decision-makers respond to expanded carbon budgets? The potential for moral hazard, using expanded budgets to justify delayed action, represents a new governance challenge created by quantum-informed projections. The co-production framework reveals that quantum-informed climate modeling is not merely a technical advance but a political intervention that reshapes the relationship between scientific knowledge and policy action. The distributional consequences we identify (Figure 7D) highlight how co-production has justice implications: reduced uncertainty may benefit some populations more than others, depending on how quantum knowledge is prioritized, validated, and applied.

b. Implications for Climate Governance

Our findings have significant implications for climate governance across multiple dimensions, revealing both opportunities and challenges for policy-making in an era of quantum-informed climate projections.

Uncertainty governance: The 30-40% uncertainty reduction in cirrus cloud feedback and 52.7% reduction in soil respiration uncertainty fundamentally alter the governance landscape for climate policy. Reduced uncertainty distributions require updated governance frameworks that can effectively utilize more precise climate information while maintaining robustness to remaining uncertainties (van der Sluijs et al., 2005). The narrowing of uncertainty creates new possibilities for risk-based decision-making, enabling more confident assessment of climate impacts and more precise targeting of adaptation investments. However, the remaining uncertainties, including those related to quantum hardware noise, emulator fidelity, and structural model errors, must still be managed. The findings suggest that uncertainty governance must evolve from simply acknowledging uncertainty to actively characterizing, communicating, and managing it. The quantum-informed approach provides a model: by explicitly quantifying quantum hardware error, emulator uncertainty, and propagation through the climate model, it enables more transparent and rigorous uncertainty characterization. This transparency enhances the credibility of climate projections in policy contexts, as decision-makers can better understand the sources and magnitude of remaining uncertainties. However, effective uncertainty governance also requires capacity-building: policy-makers, stakeholders, and the public must develop the skills to interpret and use probabilistic climate information appropriately. The physics-informed emulator architecture provides a template for making quantum-derived constraints accessible to non-experts while maintaining scientific rigor.

Carbon budgeting: Expanded carbon budgets challenge current policy narratives and require reassessment of national contributions, international agreements, and climate litigation strategies (Rogelj et al., 2019; Asayama et al., 2019). Our finding of ~2,500 Pg C larger terrestrial carbon sink by 2100 under quantum-informed projections fundamentally alters the carbon budget arithmetic that underpins the Paris Agreement. This expansion corresponds to additional emissions of approximately 9,175 $GtCO_2$, equivalent to decades of current global emissions. Such a substantial revision has profound implications for national determined contributions (NDCs): countries may need to reassess their emissions reduction pledges in light of expanded carbon budgets. International agreements, including the Paris Agreement's ratcheting mechanism, may need to be recalibrated to reflect new understanding of the carbon cycle response to warming. Climate litigation strategies may also be affected: plaintiffs and defendants may use quantum-informed projections to argue about the adequacy of mitigation targets, the fairness of burden-sharing, and the urgency of action. The expanded carbon budgets also create new policy options: with more time to achieve temperature targets, more gradual transition pathways become feasible, potentially reducing economic disruption and facilitating just transitions. However, as Rogelj et al. (2019) caution, expanded budgets also risk moral hazard—the temptation to delay action in the expectation of future technological breakthroughs. The governance challenge is to use expanded budgets to enable more ambitious, not more delayed, climate action. This requires institutional mechanisms that lock in ambitious trajectories, such as ratcheting mechanisms, independent monitoring, and transparency frameworks.

Adaptation planning: More precise regional projections enable more targeted adaptation strategies, but also raise questions about how to allocate adaptation resources across regions and populations (Hallegatte, 2009). The quantum-informed projections we describe provide not only global constraints but also regional insights through improved representation of cloud processes and soil carbon dynamics. For agricultural regions, reduced uncertainty in soil carbon loss projections (Figure 8A) enables more precise targeting of adaptation strategies, such as soil conservation practices, crop selection, and irrigation management. For permafrost regions, narrowed uncertainty in carbon release projections (Figure 8B) supports more robust planning for infrastructure adaptation and community relocation. However, the distribution of uncertainty reduction is not uniform. Our analysis (Figure 8D) reveals that while vulnerable regions (South Asia, Africa) see larger uncertainty reductions, the translation of these reductions into adaptation action depends on institutional capacity, financial resources, and political will. The governance challenge is to ensure that improved climate information actually benefits vulnerable populations rather than exacerbating existing inequalities. This requires investment in institutional capacity, participatory processes that engage stakeholders in adaptation planning, and financial mechanisms that direct resources to where they are most needed. The quantum-informed approach provides a model for more targeted adaptation: by identifying which climate uncertainties are most consequential for specific regions and sectors, it enables more efficient allocation of adaptation resources.

Climate justice: Narrowed uncertainty distributions may reduce the "uncertainty veil" that has protected some populations from political scrutiny, creating both opportunities and risks for vulnerable communities (Schlosberg & Collins, 2014). The environmental justice implications of quantum-informed projections are profound and complex. On one hand, reduced uncertainty enhances the ability to identify and quantify climate risks to vulnerable populations, supporting more targeted and effective climate justice interventions. For example, narrower uncertainty in agricultural soil carbon loss (Figure 8A) enables more precise identification of food-insecure regions and more targeted adaptation support. Narrowed uncertainty in permafrost carbon release (Figure 8B) enables better planning for relocation of high-latitude communities and compensation for climate damages. However, reduced uncertainty also creates new risks: it may expose vulnerable populations to greater political scrutiny, leading to neglect of the structural inequalities that shape climate vulnerability. The "uncertainty veil" has historically protected some populations from blame for climate impacts; its removal may expose them to new forms of political pressure. The distributional analysis (Figure 8D) reveals that economic benefits from uncertainty reduction are not evenly distributed, with high-income groups capturing disproportionate shares. This raises fundamental questions about climate justice: who benefits from improved climate information? Who bears the costs of remaining uncertainties? How can governance processes ensure that the benefits of quantum-informed projections are shared equitably? Our findings suggest that justice must be explicitly integrated into the development and application of quantum-informed climate projections, through participatory governance mechanisms, equity-focused impact assessments, and explicit consideration of distributional consequences.

4.6 Limitations and Future Research

a. Limitations

Technical limitations: Our analysis relies on simulated quantum data, and actual NISQ device results may show greater error and noise than our simulations (Preskill, 2018). The quantum kernel and VQE calculations we describe assume ideal or near-ideal quantum hardware, whereas current devices suffer from decoherence, gate errors, and readout errors that may degrade performance. While we incorporate error-aware design principles; randomized compiling, symmetry-adapted ansatze, and cross-verification, the practical implementation of these strategies on real hardware remains to be demonstrated. Furthermore, the computational cost of running quantum calculations for all relevant environmental conditions (temperature, pressure, composition) may be prohibitive even with error mitigation techniques. The physics-informed emulator approach reduces this burden, but emulator accuracy depends on the quality and quantity of training data, which ultimately comes from quantum hardware. Scalability to the full range of aerosol compositions, soil types, and climate conditions requires substantial advances in both quantum hardware and emulation methodology. Implementation in operational Earth System Models also presents significant challenges, including interface standardization, numerical stability, and computational efficiency at the global scale.

Generalizability: Our two case studies, ice nucleation on mineral dust and soil respiration temperature sensitivity may not be representative of all climate processes that could benefit from quantum constraints. Other sub-grid processes, including aerosol aging, cloud droplet activation, and ocean biogeochemistry, involve different physical and chemical mechanisms with different quantum computational requirements. The generalizability of our findings depends on whether similar quantum-derived constraints can be obtained for these processes, whether the same hybrid framework architecture applies, and whether uncertainty reductions of comparable magnitude are achievable. The fault-tolerant-inspired framework we describe provides a general template, but its application to each new process requires tailored quantum algorithm design, emulator development, and model integration. Generalization also requires investigation of additional parameterizations across the Earth System, including the carbon-nitrogen-phosphorus cycle, aerosol-cloud interactions, and cryosphere processes. The social-epistemic dynamics we observe in quantum-climate collaboration may also vary across different research communities and institutional contexts.

Social-epistemic scope: Our analysis of research community dynamics is based on published literature and documentation rather than direct ethnographic observation. This limits our ability to capture the micro-dynamics of interdisciplinary collaboration, including informal negotiation, tacit knowledge transfer, and power relations within research teams. The boundary work we describe is inferred from published accounts rather than observed in real-time. Future research should employ ethnographic methods—participant observation, in-depth interviews, and document analysis—to examine quantum-climate collaboration in practice. Such research would provide richer understanding of how epistemic cultures interact, how trust is built across disciplinary boundaries, and how institutional arrangements shape research outcomes. The social-epistemic implications of quantum-informed modeling may also vary across different institutional contexts, including academic, government, and private sector settings. Our analysis focuses primarily on academic research; the dynamics of quantum-climate collaboration in operational settings—such as national meteorological services or private climate analytics firms—may differ substantially.

Policy impact assessment: The governance implications we identify are plausible but not yet realized. The actual policy impact of quantum-informed projections will depend on how they are adopted and appropriated in political processes. Carbon budget expansions, mitigation timeline extensions, and economic risk reductions are potential rather than actual outcomes. The translation of quantum-informed projections into policy action depends on multiple factors, including IPCC uptake, national adaptation planning processes, and the political economy of climate decision-making. The moral hazard risk we identify—that expanded budgets may enable delayed action, represents a potential governance failure rather than an inevitable outcome. The actual policy impact will depend on institutional mechanisms that lock in ambitious trajectories, including ratcheting mechanisms, independent monitoring, and transparency frameworks. The distributional consequences we identify are similarly contingent: they depend on how quantum-informed projections are applied in adaptation planning, resource allocation, and compensation mechanisms. The governance challenge is to design processes that translate quantum-informed knowledge into just and effective climate action.

V. Conclusions

This research demonstrates that integrating quantum-mechanical calculations with Earth-system modeling constitutes a fundamental epistemic shift in the production and use of climate knowledge. Three principal findings emerge.

First, quantum-informed parameterizations substantially reduce uncertainty in critical processes. For ice nucleation on mineral dust, cirrus-cloud feedback uncertainty declines 30–40 %, raising decision confidence from 0.82 to 0.95 and improving governance scores by 0.8–1.3 points. For soil respiration, enzymatic constraints cut carbon-cycle feedback uncertainty by 52.7 % and expand remaining carbon budgets by ~2500 Pg C (~9175 $GtCO_2$), valued at $500–2000 trillion and extending 1.5–2.0 °C mitigation timelines by 36–94 years. Expanded budgets enable more gradual, equitable transitions yet risk moral hazard if they delay action.

Second, the approach replaces empirical fitting of parameters such as Q_{10} with first-principles activation energies (31–46 kJ mol^{-1}). This shift reduces interpretive flexibility and fosters a hybrid epistemic culture bridging quantum physics, computation and climate science, embodied in new boundary objects (Verified Quantum Kernel, Physics-Informed Emulator).

Third, narrower uncertainty enhances policy credibility and supports more targeted adaptation, but benefits are unevenly distributed. Vulnerable regions gain larger uncertainty reductions, yet economic gains accrue disproportionately to high-income groups. Realizing climate-justice outcomes therefore requires deliberate governance mechanisms that convert expanded budgets into accelerated, rather than delayed, action.

Recommendations

Scientific communities should establish interdisciplinary quantum–climate consortia that prioritise high-impact processes (ice nucleation, soil enzyme kinetics, aerosol ageing) and develop standardised interfaces with Earth-system models. Validation protocols must combine classical benchmarks, experimental data and rigorous uncertainty quantification. Open repositories of quantum-derived constraints and trained emulators, together with cross-disciplinary training programmes, will accelerate adoption and build workforce capacity. Stakeholder engagement should be embedded from the outset to ensure legitimacy and relevance.

Policy processes should integrate quantum-informed parameterisations into CMIP7 and the next IPCC cycle, revise carbon-budget methodologies to reflect the ~2500 Pg C expansion, and update adaptation frameworks with more precise regional projections. Quantum-informed evidence should be recognised in climate litigation, while international coordination and capacity-building must guarantee equitable access for developing countries.

Governance and justice require environmental-justice assessments of the distributional consequences of narrowed uncertainty, participatory mechanisms that give affected communities voice, and transparent uncertainty communication that distinguishes reducible from irreducible uncertainty. Continuous monitoring of social and institutional impacts, coupled with responsible-innovation principles, will help ensure that expanded carbon budgets drive accelerated rather than delayed action and that benefits are equitably shared.

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