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Robust assessment of Solar Radiation Modification risks and uncertainties must include shocks and societal feedbacks

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Abstract. Conventional climate scenarios omit fast-timescale human-system dynamics like policy rollback or economic shocks. The climate system's slow response to GHG emissions allows these 'fast' terms to be averaged out, a simplification that obscures event-driven risks. Solar Radiation Modification (SRM) invalidates this assumption: rapid, sub-decadal climate responses couple directly to fast political and societal dynamics. This creates an analytical problem: acknowledged primary risks of SRM (termination shock, geopolitical conflict, moral hazard) cannot be resolved in smooth pathways but require an event-based perspective. To address this, we propose the Solar Radiation Modification Pathway (SRMP) framework, introducing five typologies that define governing logic for human-physical system interactions across timescales. We illustrate how SRM-driven shocks could fundamentally divert trajectories from static SSP narratives, revealing limitations in frameworks that assume fixed socio-political contexts. The SRMP framework serves as a diagnostic tool identifying what must be represented for adequate SRM risk assessment. By naming dynamics that current architectures cannot capture, it establishes minimum conditions for assessment that represents the fundamental risks of real-world SRM deployment. If SRM is evaluated primarily through idealised "best-case" scenarios, the research community risks providing a systematically distorted evidence base for decisions that could prove irreversible.

1 Introduction

The continued inability to bend the emissions curve and achieve emission reductions necessary to avoid severe climate risks has intensified interest in Solar Radiation Modification (SRM) as a potential, albeit controversial, component of the climate response portfolio. Proposed SRM techniques, particularly Stratospheric Aerosol Injection (SAI), could theoretically cool the planet rapidly at a relatively low direct cost compared to the anticipated economic damages of climate change (Heutel

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et al., 2018; Smith, 2020; Reynolds and Wagner, 2020; Smith and Wagner, 2018; Nordhaus, 1992). However, this apparent simplicity obscures a profound depth of uncertainty and risk. SRM would not restore a past climate but create one that is distinctly different, with potential for unintended and uneven consequences, including altered precipitation patterns (Simpson et al., 2019), atmospheric chemistry changes (Nowack et al., 2016), and disruptions to ecosystems (Jin et al., 2022; Cao, 2018).

Assessing these unique risks presents a fundamental challenge, as the current research landscape is split between two largely disconnected fields. On the one hand, Earth System Models (ESMs) provide invaluable insight into the physical climate response, but typically rely on highly idealized, "best-case" scenarios that assume perfect global cooperation and uninterrupted deployment (Visioni et al., 2024; Kravitz et al., 2015; Jones et al., 2013), such as a "peak-shaving" pathway to control temperatures during a period of temperature overshoot (Figure 1a). On the other hand, socio-political studies and simple cost-benefit models which have been used to explore SRM human-climate evolution (Belaia et al., 2021; Heutel et al., 2018, 2016; Moreno-Cruz and Smulders, 2017) often oversimplify the complex, regional climate dynamics that would drive real-world outcomes by reducing damages to simple functions of global temperature (Bahn et al., 2015; Heutel et al., 2018; Smith, 2020; Reynolds and Wagner, 2020; Smith and Wagner, 2018; Nordhaus, 1992).

Meanwhile, the large, process-based Integrated Assessment Models (IAMs) used for mainstream mitigation analysis (Wilson et al., 2021) have been little used for this purpose, and are to some degree architecturally incompatible with SRM's core risk profile, as their cost-optimizing logic is mismatched with a problem defined by non-optimal, event-driven, geopolitical risks. Implementing SRM in current IAM frameworks without constraint would likely lead to cost-effective large-scale deployment (a backstop technology), as identified by Nordhaus (Nordhaus, 1992; Helwegen et al., 2019).

This leaves the most critical, policy-relevant risks of SRM, such as governance failure and geopolitical conflict (Pezzoli et al., 2023; Cherry et al., 2024), abrupt termination (Parker and Irvine, 2018), and regional impact disparities (Heyen et al., 2015) un-modeled by either ESM or IAM paradigms.

In this paper, we argue these gaps cannot be addressed by simple extension of existing frameworks; conventional climate scenarios, developed for modelling the effects of anthropogenic greenhouse gas emissions and their co-emitted species, do not resolve fast-timescale, stochastic human-system dynamics like political failures, conflicts, or economic shocks. This simplification can be justified (for greenhouse gas mitigation modeling) by societal and techno-economic as well as physical considerations. On the societal and techno-economic side, future emission trajectories are dominated by long-term developments including population dynamics, economic development and emission intensity of the economy. Changes to the emission intensity, i.e. in a process of a structural decarbonisation transformation will be determined by the temporal dynamics of technological change and the often multi-decadal lifetime of existing infrastructure and material stocks (Keppo et al., 2021; van Vuuren and Riahi, 2008).

Even more important for the argument we are developing here are physical considerations: The climate system's response to GHG emissions is slowly emerging over multi-decadal horizons. This lag effectively enables "fast terms" to be averaged out when modeling the climate effect of emissions pathways. In fact, even a global event such as the COVID-19 pandemic had very limited impact on the global climate (Forster et al., 2020). These properties allow the climate community to develop

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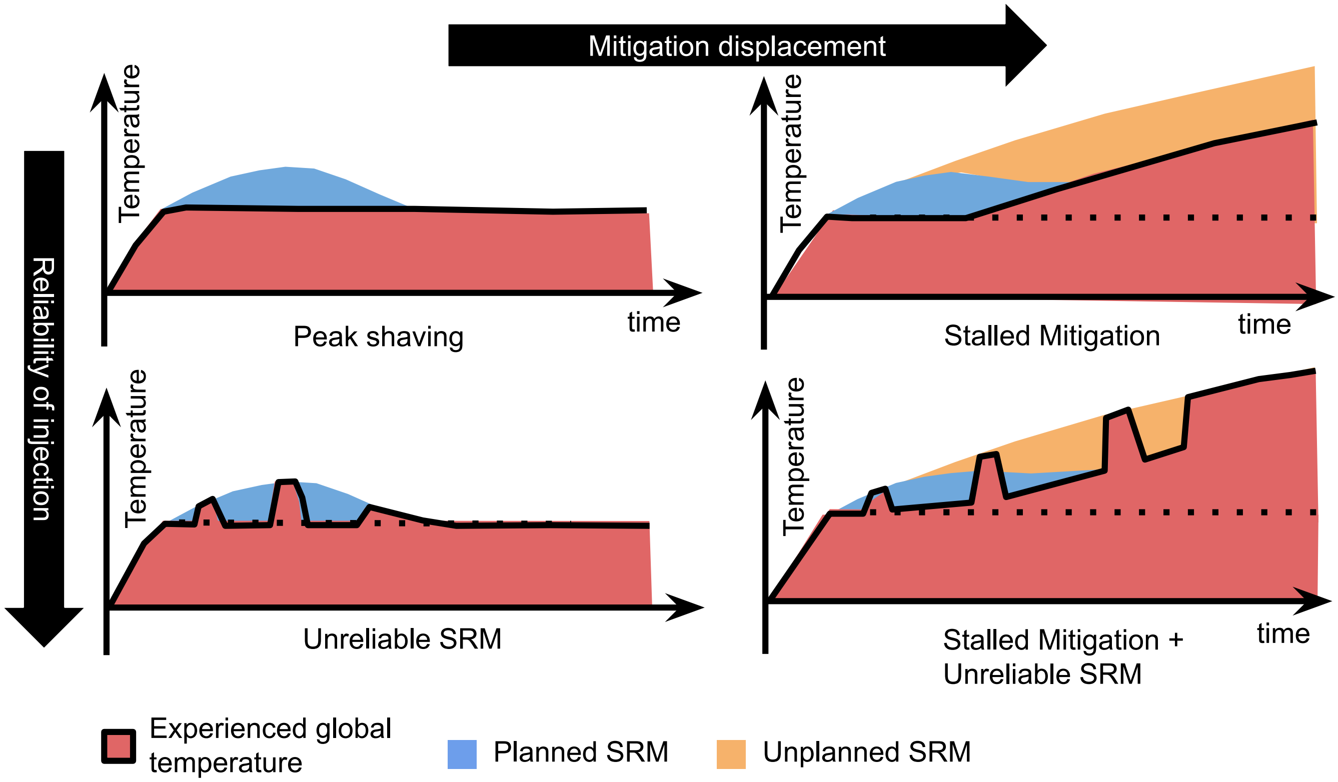

Figure 1. Conceptual illustrations of unresolved risks in current ESM-based SRM modeling efforts. Plots indicate stylised temperature as a function of time. The top left scenario indicates a conventional peak-shaving scenario such as G6-1.5K-SAI (Visioni et al., 2024). Scenarios in the right column are subject to mitigation displacement, and experience an extended overshoot with protracted need for SRM. Solid black lines indicate the temperature trajectory, while dashed lines indicate the planned temperature pathway. Scenarios on the bottom row are subject to unreliability in SRM capabilities, experiencing interruptions, temperature shocks and potential permanent loss of capacity to continue injection.

and model emission scenarios up to the end of the century or even beyond despite the deep uncertainties in socio-economic development.

However, decisions and climate effects for SRM are *not* subject to this timescale separation. Its rapid, sub-decadal climate effect, whether real or perceived, through co-occurrence with annual scale weather variability, couples the climate response directly to fast, societal and political dynamics that can impact, for example, the stability of deployment (Figure 1c). The climate response becomes as fast as the political processes themselves. Consequently, these fast-timescale events (e.g. a political agreement failing, a unilateral action beginning) are no longer noise; they become first-order drivers of risk.

Compounding this challenge is a fundamental issue of detectability and attribution. For any realistic SRM deployment, climate signals must be detected against the background noise of natural variability (Seidel et al., 2014)—an irreducible un-

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certainty that can confound perception of SRM effects in either direction. Because governance operates on the same rapid timescales as these fluctuations, misattribution becomes a primary mechanism for governance failure (Section 4.1.1).

Furthermore, SRM challenges the (stylised) assumption that the world's socio-political evolution can be externally prescribed to follow a single Shared Socioeconomic Pathway (SSP). These SSPs are stylised in nature, and the absence of e.g. a climate impact feedback on the assumed socio-economic development, raises important questions also when using this concept in a GHG emission regime only (Meinshausen et al., 2024). But, given the fast response time-scales in a SRM regime, this simplification becomes a particular concern. A unilateral SRM deployment, for example, would hardly be aligned with a functioning multilateral world order, and could, for example, lead to disintegration into regional rivalry regimes. Similarly, SRM deployment may itself affect the mitigation trajectory (moral hazard) leading to higher emissions (Fig. 1b).

To structure this new, complex problem space, we introduce the Solar Radiation Modification Pathway (SRMP) framework. The SRMP is a conceptual tool designed to provide a "common language" and a blueprint for the new assessment approaches required. We define five core SRMP typologies (Figure 4) that provide the governing logic for these fast, stochastic feedbacks. We then demonstrate how these SRMPs can interact with the prognostic state, allowing SRMP-governed events to alter the sociopolitical context for the scenario. This framework provides a new, structured method for exploring the fast, non-ideal, and event-driven futures that define the SRM problem, offering a mechanism for integrating stochastic shocks into long-term climate scenarios.

2 A typology for climate-human system feedbacks

Figure 2 presents a conceptual blueprint for an integrated assessment system designed specifically to capture the coupled socio-technical and political dynamics of SRM. This blueprint focuses on the necessary functions and their interconnections, rather than being constrained by the architectures of any existing model classes. The system is defined by three interconnected systems, which are visualized as distinct "loops":

1. **Slow Climate-Change-Mitigation Loop:** This is the conventional assessment loop that current IAMs are designed to simulate. GHG emissions from the Economic & Energy Systems module drive changes in the Earth System & Impacts module. In turn, the slowly emerging (∼30-year lag) and detectable impacts feed back to inform mitigation policy.

2. **Fast Governance-Deployment Loop:** This is the first critical missing element from current modeling frameworks. Here, rapid climate responses and shocks from SRM activity, or extreme weather or climate events arising from internal variability but misattributed to that activity, can feed back on a rapid (sub-decadal) timescale into geopolitical and governance dynamics. This feedback drives "Deployment Control", which is now treated as a sudden event (e.g., a governance failure, unilateral action) rather than a smooth, optimal choice. This bi-directional loop captures the primary mechanism for termination or initiation shocks, as well as the confounding potential of irreducible uncertainty stemming from internal weather variability, where greenhouse gas driven climate change alone is expected to produce unprecedented variability (Olonscheck et al., 2021). Automated monitoring and response systems to manage sub-annual

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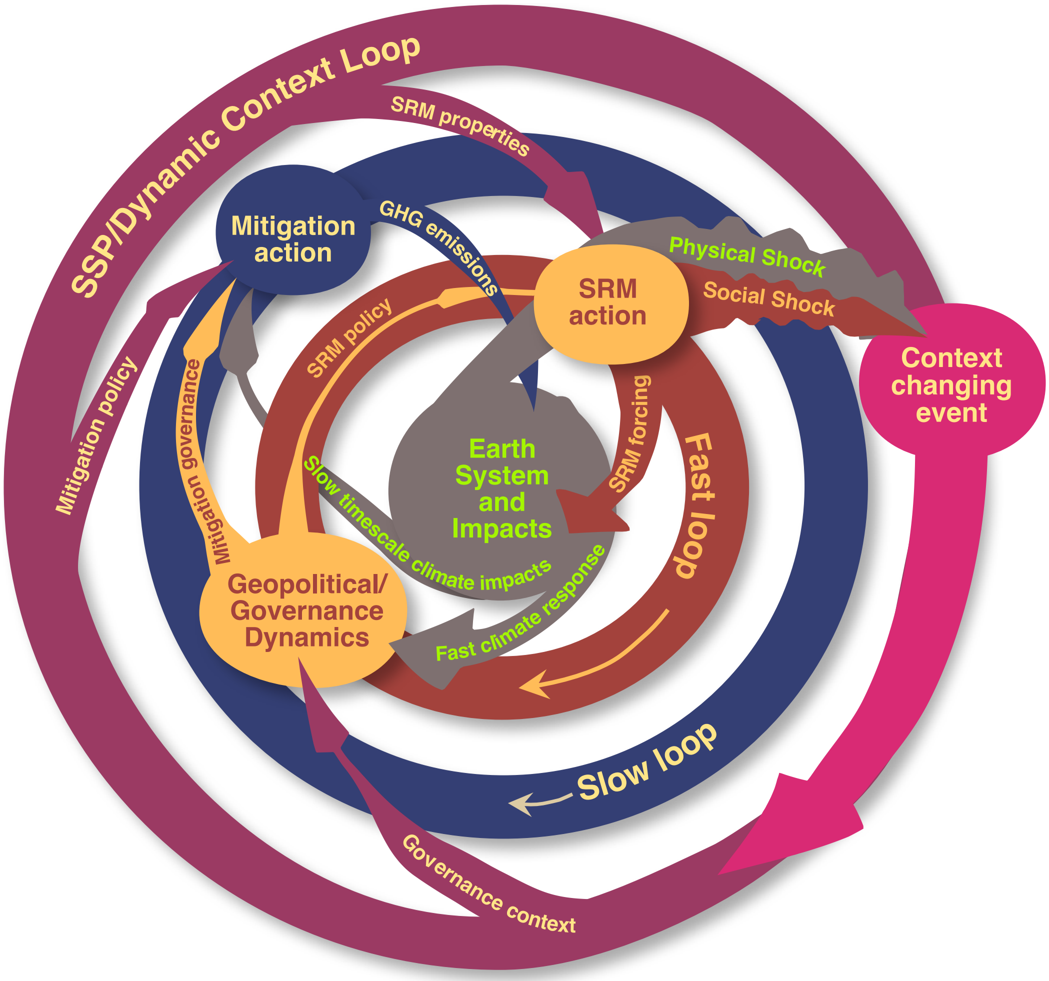

Figure 2. Illustration of the interactions required to model the coupled SRM dynamics. The grey circle at the centre indicates the Earth System which can be influenced by, and can exert feedbacks on, different "loops". The "Slow Loop" (blue) describes the conventional IAM/climate modeling loop on the multi-decadal timescale while "Fast Loop" (brown) components describe human-climate feedback on the annual timescale driven by SRM implementation, while the "Dynamic context loop" (purple) describes potential feedbacks which modulate the socioeconomic background state.

variability could further compress implementation timescales while introducing algorithmic opacity and novel failure modes that would complicate accountability and human oversight.

3. **Dynamic Context Loop:** This loop represents a novel, prognostic element which is necessary to represent potential moral hazard effects. In the conventional SSP framework, the context is exogenously defined by the choice of SSP. In contrast, SRM outcomes, such as an emerging geopolitical conflict, can feed back and dynamically alter the socio-

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political "State", creating conditions incompatible with initially assumed contextual properties (for example, generating barriers to mitigation or degrading adaptive capacity).

Core elements of this system need to be defined by socio-political scenarios, but as this new blueprint illustrates, existing frameworks that treat the socio-political context as static and exogenous are insufficient. The system's behavior, including the evolution of the context itself, must be modeled and assessed. This highlights the need for a structured, systematic method to define these driving scenarios, a task for which we propose the Solar Radiation Modification Pathway framework.

3 Beyond the SSP framework

The Shared Socioeconomic Pathways (SSPs) were designed to "facilitate research that integrates climate and societal futures" and have been highly successful in this role. The SSPs are explicitly defined as "reference" pathways describing society's evolution "in the absence of climate change or climate policies"—intentionally exogenous "archetypes" that provide boundary conditions onto which climate impacts and interventions are applied (O'Neill et al., 2014). This framework separates socio-political context (SSPs) from intervention logic through "Shared climate Policy Assumptions" (SPAs), such as carbon pricing, that operate within a given SSP context. This separation works well for slow, managed mitigation policies. However, SRM challenges this design: its rapid feedbacks mean interventions can fundamentally alter the context itself, not merely operate within it. To model SRM's three-loop dynamics (Figure 2), we must therefore reconceptualize SSPs and interventions as dynamically interacting.

The SSPs define the world's socio-political context and capacity (O'Neill et al., 2014). Subsequent extensions to the framework, such as adding sectoral detail (Leimbach et al., 2023), inequality dimensions (Rao et al., 2019), or governance indicators (Andrijevic et al., 2020), enrich the description of the "state" but do not fundamentally change its static logic. While existing SSP-SPA combinations reveal tensions (stringent mitigation in fragmented worlds (SSP3), or unrepresented impact feedbacks at high warming (Hausfather and Peters, 2020)) these have not required fundamental framework revision.

However, we argue that SRM presents greater challenges which make it fundamentally incompatible with this "static archetype" model. It is not merely a "policy" (an SPA) that is applied *onto* an SSP. Its core risks are fast-feedback mechanisms that can alter the world's actual socio-political trajectory, pushing it off its original path. There are two core problems with applying the conventional SSP-SPA framework to SRM:

1. **The Fast Loop Problem:** A conventional SPA is assumed not to interact with the underlying SSP. An SRM intervention is defined by fast-timescale, event-driven outcomes. A termination shock, for example, is not a "policy"; it is a *governance failure* that couples directly with a rapid climate response (Parker and Irvine, 2018). A static SSP, by design, separates policy (SPA) from context (SSP) and has no mechanism for this kind of fast, coupled, unpredictable *event*.

2. **The Dynamic Context Problem:** A mitigation SPA does not change the core logic of an SSP (e.g., a high mitigation SSP5 world remains an SSP5 world, with carbon pricing solutions which are consistent with this narrative). SRM, however, has the potential to shift the context. A "moral hazard" feedback, where successful SRM deployment even

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under a mitigation focussed narrative (SSP1) structurally removes the incentive to decarbonize, is a mechanism that can dynamically entrench a high-emissions state. This is an example of the "Dynamic Context Loop" (Figure 2) where the intervention can cause the world's socio-political trajectory to evolve.

Moral hazard risks apply in a similar way to potential large scale CDR (Moioli et al., 2025). Yet, there are important distinctions. Firstly, large scale CDR applies to emissions and within the accounting logic of established frameworks such as fair share assessments based on a carbon budget that can be extended appropriately (Pelz et al., 2025). An application of SRM would decouple the emissions-to-warming relationship in a fundamental way, thereby risking undermining policy processes and international governance regimes based on it. Secondly, the issue of scalability may apply very differently to SRM and CDR. CDR options will be subject to a range of technological or sustainability constraints (Prütz et al., 2024) and physical limits. Also any potential SRM deployment would face constraints (Hack et al., 2025), but these may not put fundamental limits to its scalability.

These distinctions point to a more fundamental difference: the timescale of feedback. CCS or CDR deployment challenges would emerge gradually over multi-decadal timescales as technological, economic, or sustainability constraints become apparent. This allows policy responses and framework adjustments on commensurate timescales, remaining within the "Slow Loop" logic of conventional IAM frameworks and compatible with static SSP assumptions. SRM's moral hazard, by contrast, operates through rapid, sub-decadal climate responses coupling directly to fast political dynamics. Successful SRM deployment could trigger immediate reductions in perceived climate urgency and mitigation ambition: a "Fast Loop" feedback (Figure 2) that conventional frameworks, including the static SSP assumption, are architecturally unable to represent. This is the "Dynamic Context Loop" where the intervention can cause the world's socio-political trajectory to evolve in ways that CCS/CDR dependencies, while creating risks, do not.

These challenges are, in fact, a known frontier for the SSP framework. O'Neill et al. (2020) identify a key need to "consider how scenarios can best account for future shocks", such as pandemics or disruptive events ("wildcards"). That review explicitly discusses how such shocks could cause a "transformational change" that shifts a development pathway toward a different socioeconomic state. Furthermore, while the use of independent dimensions for socioeconomics (SSP), policy (SPA), and impacts (RCPs) may have made sense at the time the SSPs were originally envisaged, climate policy and climate impacts now have discernable impacts and can no longer be justifiably assumed to be independent of the SSPs.

SRM, therefore, acts as a "stress test" that highlights the limitations of the static SSP model, and motivates the need for more dynamic frameworks. To model SRM, we must generalize the scenario framework from one based on static, pre-defined pathways to one that can handle dynamic, history-dependent trajectories that move *within* the state space defined by the SSP archetypes. This requires a formal decoupling of roles, which we introduce as the "State vs. Driver" model.

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4 Illustrating State-Driver Mechanisms

We propose that in order to model SRM (or other systems governed by fast-acting, sudden dynamics), we must formally decouple the two roles of "State" and "Driver". This model allows us to conceptually represent the two missing loops in Figure 2.

4.1 The SRMP "Driver" Properties

The Solar Radiation Modification Pathway (SRMP) is the "Driver". It is *not* a new SSP. It is the governing logic of the interaction between fast- and slow-feedback systems. It is a static typology (here we define five, Figure 4a to e) that defines the nature, rules, and probability of the stochastic events that can occur and power the "Fast" Governance-Deployment Loop.

The SRMP "Driver" logic is defined by a set of properties or dimensions (Figure 3). These govern the behavior of the fast operational and context feedback loops (Figure 2), so we group these properties into two distinct categories: **Fast Loop Driver Properties** (operational rules) and **Context Loop Driver Properties** (socio-political logic):

4.1.1 Fast Loop Driver Properties (Operational Rules)

These properties define the physical, operational, and strategic rules of the SRM intervention itself. They are the parameters that govern the "Fast" Governance-Deployment Loop.

- **Interruption Risk:** The probability of a stochastic, rapid cessation of deployment. This represents the technical reliability or political fragility of the deployment system and is the primary mechanism for a "termination shock" event.
- **Deployment Regionality:** The physical and strategic nature of the injection. This property defines whether the deployment is global, optimized for a specific coalition, or purely unilateral.
- **Operational Inefficacy:** The technical success of the deployment in achieving its intended climate forcing target. High inefficacy represents a flawed or sub-optimal implementation.
- **Detection/Attribution Uncertainty:** The degree to which climate effects of SRM can be distinguished from natural variability and correctly attributed to the intervention. For realistic deployment scales, irreducible uncertainty from sub-decadal internal variability can confound perception of SRM effects in either direction, masking actual impacts or falsely attributing unrelated events to SRM activity. This creates a critical risk pathway: the Fast Governance-Deployment Loop (Figure 2) responds to *perceived* climate effects, meaning misattribution can trigger governance responses (termination, escalation, counter-deployment) independent of actual SRM efficacy.

4.1.2 Context Loop Driver Properties (Socio-Political Logic)

These properties define the underlying socio-political *logic* or *intent* of the SRMP "Driver." They are the specific mechanisms that generate "shocks" which can create incompatibilities between actual system dynamics and the assumed SSP "State".

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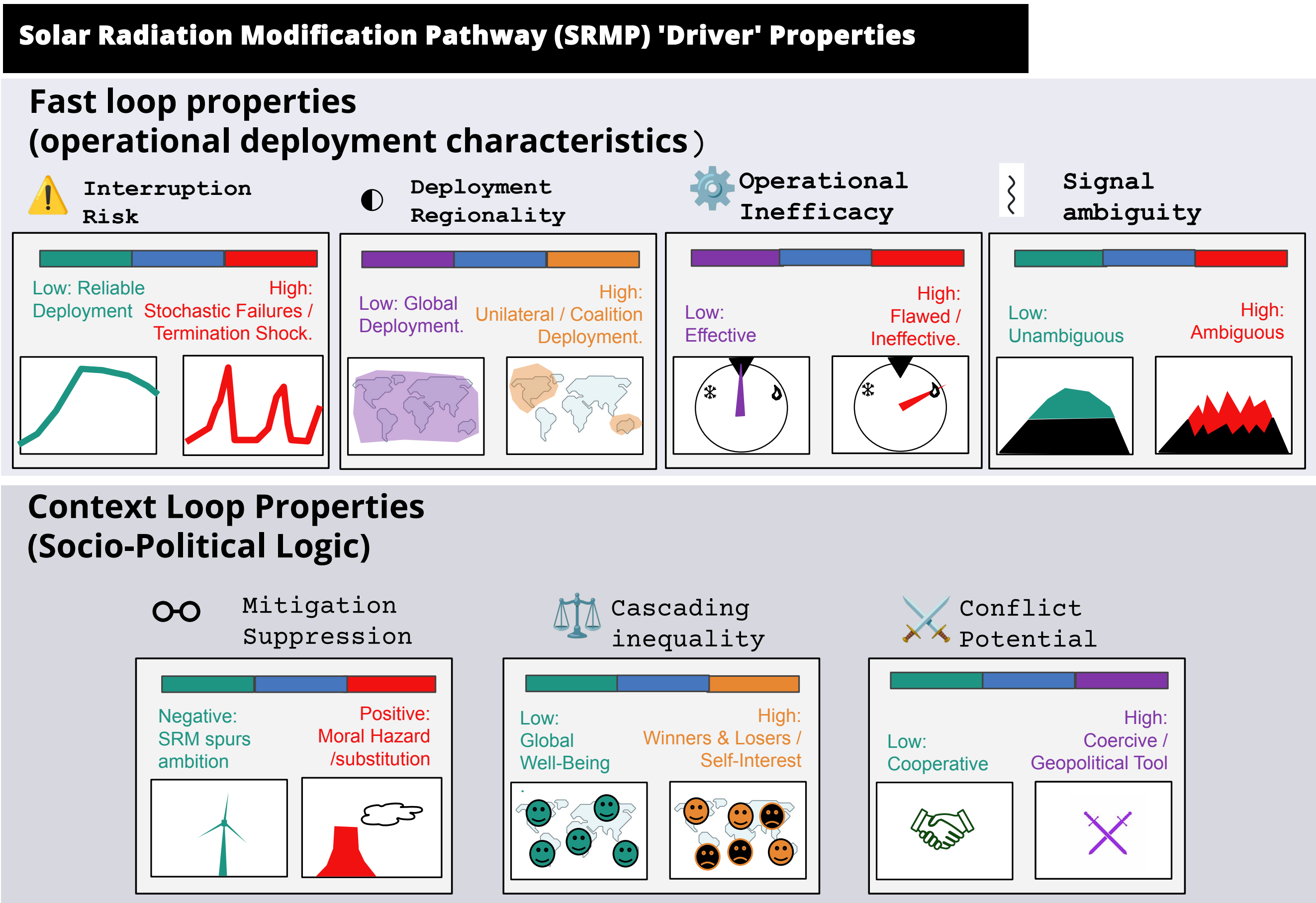

Figure 3. A Visual Glossary of the seven Solar Radiation Modification Pathway 'Driver' Properties. This figure provides a visual explanation for each of the seven properties used to define the SRMP "Driver" typologies (shown in Figure 4). The properties are grouped into two categories: **Fast Loop Driver Properties** (top row), which define the physical and operational rules of the intervention, and **Context Loop Driver Properties** (bottom row), which define the socio-political logic that can generate dynamics incompatible with assumed SSP properties.

– **Mitigation Delay:** Defines the "Driver's" logical relationship with decarbonization ambition. A high positive value represents a logic of "Substitution" where SRM success removes political incentives for emissions reductions (a moral hazard dynamic), while a negative value represents a logic of "Spurring Ambition" where SRM awareness galvanizes stronger mitigation efforts. These dynamics affect policy ambition (SPA) directly and can indirectly reshape socio-political context by altering the perceived urgency of climate action and the political coalitions around decarbonization.

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- **Inequality Potential:** Defines the "Driver's" tendency towards inequitable outcomes. A low value represents an opimisation for global well-being, while high values optimise for self-interest, creating winners and losers, generating dynamics inconsistent with equitable governance assumptions.

- **Conflict Potential:** Defines the "Driver's" geopolitical posture. A low value represents a "Cooperative" logic, while a high value represents a "Coercive" logic where SRM is treated as a geopolitical tool, generating dynamics inconsistent with multilateral cooperation assumptions.

4.2 SRMP "Driver" Typologies

The SRMP *typologies* combine a set of properties to produce different dynamical behaviours and risk profiles, conceptually illustrated in Figure 4. These serve as a basis for scenario development or as an analytical lens for examining existing SRM research and proposals and identification of understudied risk combinations. Here we propose five typologies:

SRMP-a: The Idealized Typology: a best-case "peak-shaving" SRM implementation (Figure 1): a globally coordinated, technically proficient, and time-limited deployment. Fast Loop Properties are benign, defined by low Operational Inefficacy and low Interruption Risk and Deployment Regionality. Its Context Loop Driver Properties are similarly optimistic, with low Conflict Potential and low Inequality Potential (optimizing for global well-being). Critically, it has low mitigation suppression and SRMP-a realisations could even represent accelerated mitigation with SRM, following the logic that a limited, cooperative deployment could galvanize political will, catalyzing stronger mitigation ambition and reinforcing sustainability-oriented governance. Detection/Attribution Uncertainty is **low** due to global deployment at sufficient scale to produce clear signals, and cooperative frameworks that enable sustained monitoring and attribution networks. GeoMIP CMIP7 simulations which simulate controlled SRM execution with finite duration while meeting long term mitigation goals fall into this category (Visioni et al., 2024).

SRMP-b: The Imperfect Cooperation Typology: a less optimistic, "muddle-through" typology. It describes a deployment that occurs under a global framework but is flawed by technical challenges, implementation gaps, and regional disagreements. All its properties, in both the Fast Loop (e.g., Interruption Risk) and Context Loop (e.g., Conflict Potential), are set to intermediate levels. This Driver represents a world of flawed global governance where the mitigation suppression is moderate, creating the potential for some mitigation reduction associated with SRM implementation. Detection/Attribution Uncertainty is **medium**, as implementation gaps and regional disagreements complicate monitoring coordination and introduce additional noise into attribution.

SRMP-c: The Conflict Typology: a high-risk implementation where SRM becomes a tool for competing geopolitical blocks, featuring a unilateral or regional strategy. Its logic is defined by high-risk *Fast Loop Properties*, including high Deployment Regionality (unilateral) and a high Interruption Risk (due to political instability and potential counter-deployments, leading to "unreliable" SRM behavior illustrated in Figure 1). These properties are governed by its Context Loop Driver Properties: a high Conflict Potential (coercive) and a high Inequality Potential (self-interest). Detection/Attribution Uncertainty is **high** due to regionally concentrated deployment, potential counter-deployments creating complex interference patterns, and

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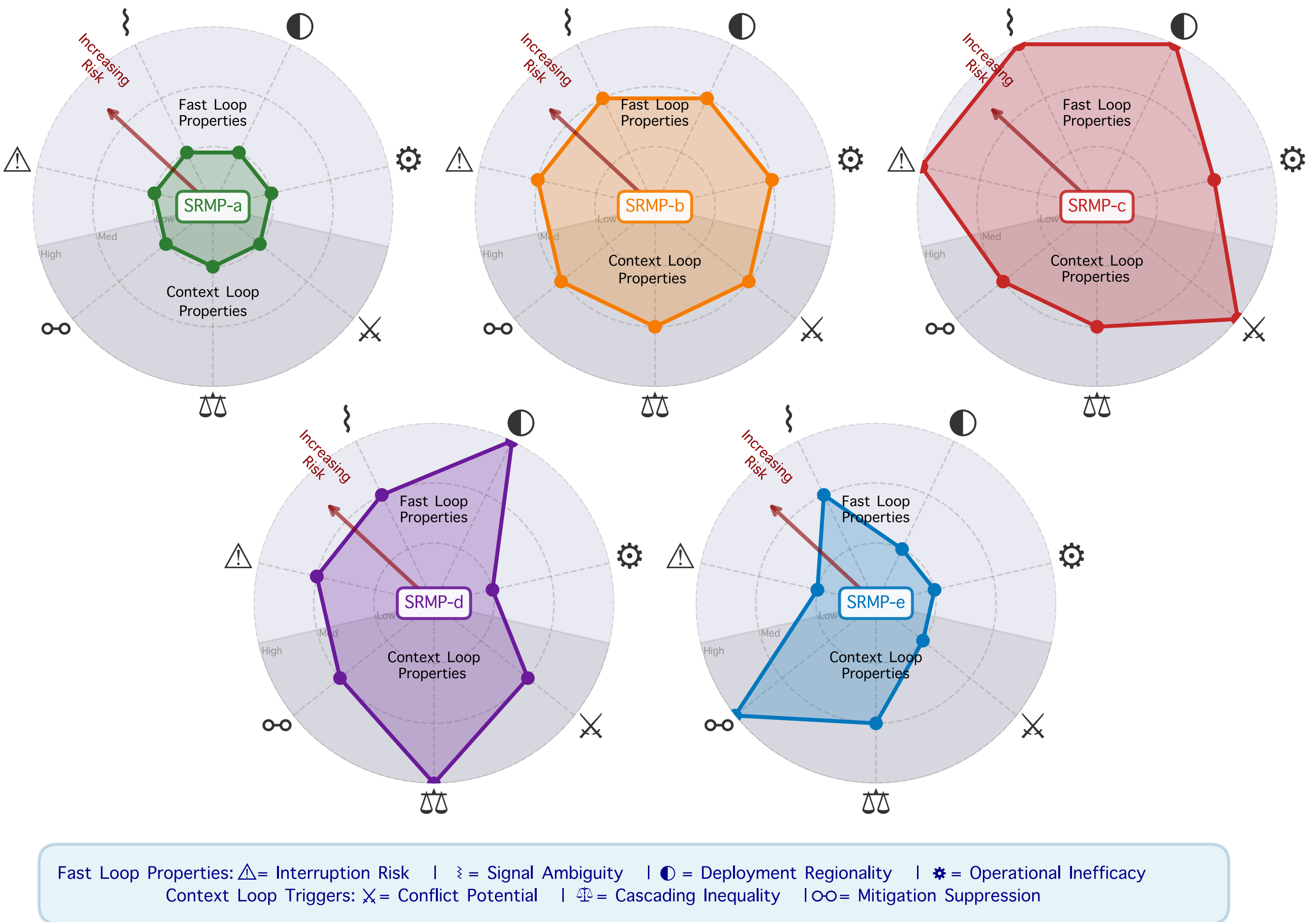

Figure 4. The Five SRMP 'Driver' Typologies. This figure illustrates the five SRMP (Solar Radiation Modification Pathway) typologies. Each typology is presented as a radar chart, where distance from the center indicates increasing risk on a given axis, defining the governing logic of the feedback system. The 'Driver' properties are separated into two categories: Fast Loop Driver Properties (operational rules governing stochastic events like interruption risk) and Context Loop Driver Properties (the socio-political logic, such as Mitigation Delay or Conflict Potential, that can generate dynamics incompatible with assumed contextual properties).

lack of cooperative monitoring frameworks. This "Driver" generates dynamics fundamentally inconsistent with cooperative governance assumptions.

SRMP-d: The Free Driver Typology: an inequality-driven logic where SRM is optimized by a specific coalition for its own interests, externalizing risks and exacerbating global inequalities. Its Fast Loop Properties are defined by high Deployment Regionality (optimized for a coalition) and high Operational Efficacy (but only for that coalition). This is distinct from SRMP-

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c, as its logic is governed by its primary Context Loop Driver Property: high Inequality Potential (explicitly creating winners and losers). Detection/Attribution Uncertainty is **high** globally (though lower for the coalition region), as coalition-optimized deployment creates regionally heterogeneous signals that are difficult to attribute outside the target region, exacerbating perceptions of inequity. This "Driver" generates dynamics that institutionalize climate inequality, creating conditions inconsistent with equitable development assumptions.

SRMP-e: The Moral Hazard Typology: the "ultimate moral hazard" case, a high-stakes gamble where SRM is technically successful but fully substitutes for mitigation. It is unique because its Fast Loop Properties are deceptively "idealized": Interruption Risk is low, deployment is global, and Operational Efficacy is high. Its danger lies entirely in its primary Context Loop Driver Property: a high Mitigation Delay (illustrated by the "stalled mitigation" pathway in Figure 1). The "Driver" logic is substitution. Detection/Attribution Uncertainty is **medium**, while technical deployment is effective and global (aiding detection), the need to attribute climate outcomes to SRM versus continued emissions reductions creates attribution challenges that can reinforce substitution logic. The success of the Fast Loop operation is the very "shock" that structurally removes decarbonization incentives, creating conditions inconsistent with ambitious mitigation pathways and potentially entrenching fossil-fuel dependence.

4.3 The "State": Context Incompatibilities

As argued in Section 3, the SSP framework's static context assumptions fail for SRM because rapid climate responses couple directly to fast governance dynamics, and because SRM-driven outcomes can fundamentally alter the socio-political context itself. This creates four categories of potential incompatibility with assumed contextual properties:

1. **Governance fragmentation risks:** Unilateral actions or deployment failures could fundamentally alter international cooperation structures.
2. **Mitigation coupling risks:** Deployment success or failure could structurally shift decarbonization incentives (moral hazard or ambition).
3. **Equity disruption risks:** Regionally heterogeneous impacts could institutionalize new patterns of climate inequality.
4. **Adaptive capacity shifts:** SRM outcomes could enhance or degrade societies' capacity to respond to future climate risks.

These are diagnostic categories identifying how SRM could create incompatibilities with assumed contextual properties. A world experiencing SRM-driven governance collapse has fundamentally different trust dynamics, institutional capacity, and vulnerability profiles than the SSP assumed at assessment outset, yet current frameworks provide no mechanism to represent this endogenous context evolution. This limitation is not unique to SRM—pandemics, technological breakthroughs, and geopolitical shocks similarly violate static context assumptions, but SRM's fast feedback makes the problem unavoidable for risk assessment.

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5 Implications for the Modeling Community

The conventional assessment pipeline, characterized by a linear sequence of IAM, ESM and Impact models, is conceptually unsuited for evaluating SRM (Figure 5). Furthermore, the fixed socio-political context (the SSPs) restricts the simulation of SRM-driven context shifts that can be considered as dominant, first-order risks of SRM as the primary mechanisms for risks like termination shock, geopolitical conflict, and moral hazard.

The “State vs. Driver” model (Figures 3, 4, and 5) is not a modelling prescription but a diagnostic framework that identifies *what must be represented* for any adequate SRM assessment. It reveals three categories of dynamics that current architectures cannot capture: stochastic event-driven shocks (the “Fast Loop”), endogenous context evolution (the “Dynamic Context Loop”), and their coupling to slow mitigation pathways. Any future assessment approach – whether through novel model development, adaptation of existing tools, or entirely new methodologies – must grapple with these representational requirements.

The most critical missing element is the “Fast Loop”. Current models average over or entirely omit fast-timescale human processes and decision-making, particularly those related to governance, geopolitical strategy, and political failure. Any adequate assessment framework must find ways to represent these dynamics – though whether this is achieved through explicit simulation, scenario-based exploration, or other methodological approaches remains an open question.

This “Fast Loop” logic is what generates the stochastic events and system shocks (such as a governance collapse, an abrupt termination, or a unilateral deployment) that define the primary risks of SRM. Because these risks are probabilistic, not deterministic, assessment can no longer rely on a few “best-guess” or optimal pathways. Instead, this new modeling approach will necessitate large ensemble simulations to explore the probability distributions of different outcomes.

The SRMP framework generalizes this by abandoning the assumption of a single, static trajectory. It treats the socio-political ‘State’ as dynamic, recognising that SRM-driven shocks can generate conditions incompatible with initially assumed contextual properties. Future models could operationalize this “Dynamic Context Loop” (Figure 2) by enabling stochastic shocks (Figure 5) to alter socio-political parameters endogenously (for example, a governance failure could degrade cooperation assumptions, or successful deployment could erode mitigation ambition).

5.1 Implications for modelling of SRM

This paper does not prescribe a specific modeling solution. The “State vs. Driver” architecture (Figure 5) is a conceptual blueprint, and we encourage a diversity of approaches to operationalize it such as novel geopolitical and strategic models (e.g., game theory (Pezzoli et al., 2023), and agent-based models (Castro et al., 2020)). However, even if these representational requirements are met by novel frameworks, a question remains on how generated pathways should be evaluated. The cost-optimizing logic that underpins conventional IAMs is inappropriate for a problem defined by non-optimal, event-driven risks, yet the alternative decision-theoretic foundation remains undefined. The framework we present here identifies what must be *represented*; it does not resolve what constitutes an *acceptable* or *preferable* outcome under deep uncertainty.

A possible modelling approach for the “Dynamic Context Loop” might be to simulate explicit transitions between named SSP states. However, this would be challenging - the SSPs are coherent narratives with internally consistent assumptions

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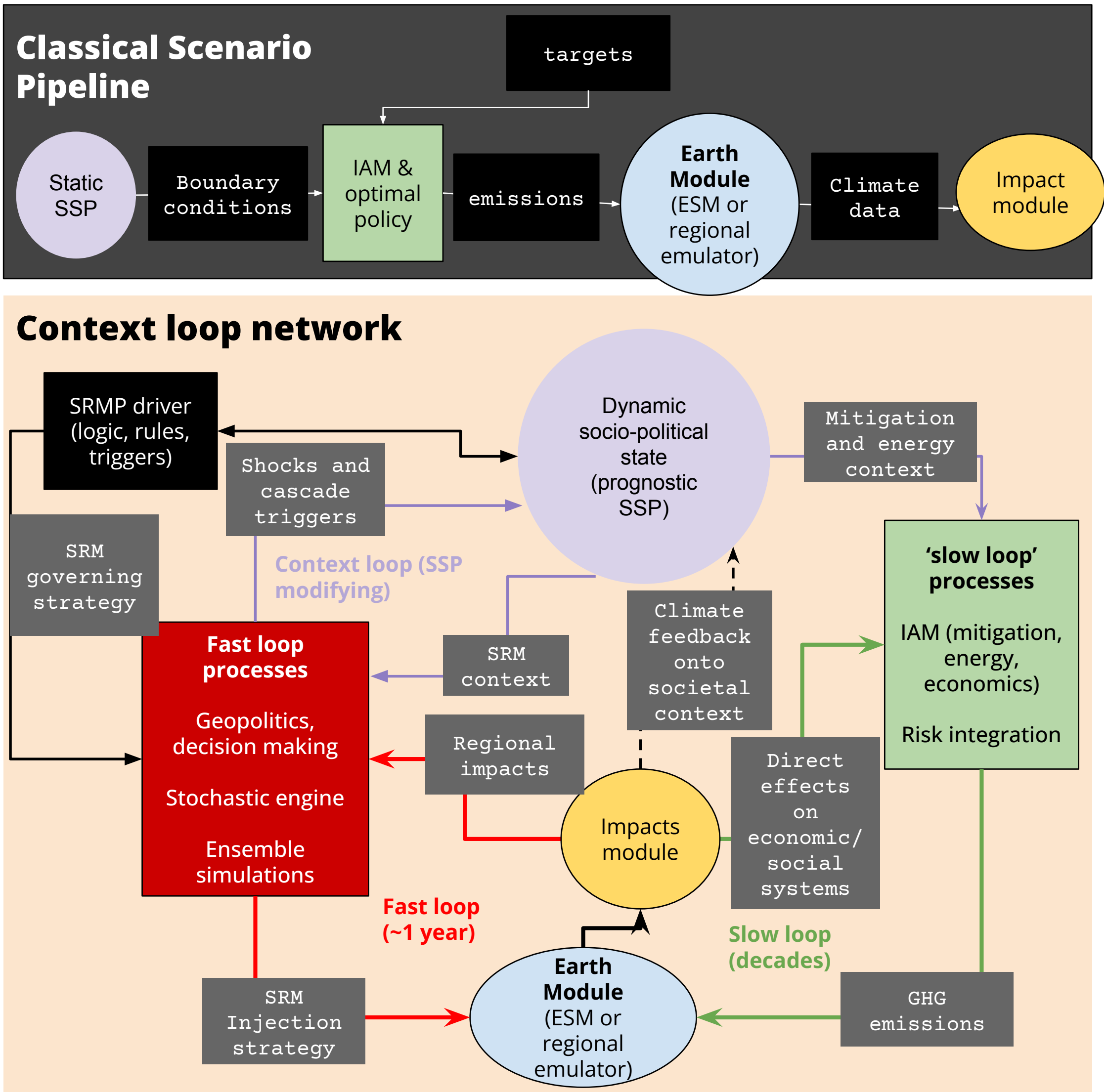

Figure 5. Comparison of Conventional and Proposed Assessment Architectures. The (A) Current Conventional Pipeline is linear and static. It relies on a Static SSP as an exogenous boundary condition for a Process IAM, which in turn provides emissions for an ESM, with Impact Assessment as the final endpoint. The (B) Proposed context loop network is iterative and dynamic. It is built on three interconnected loops (Figure 2) and the "State vs. Driver" concept. The SRMP 'Driver' provides logic to a Stochastic Engine (the "Fast Loop", timescale of years), which generates regional, stochastic deployment scenarios. The Earth System & Impacts Module (which can be an ESM or emulator) resolves regional impacts, which then feed back to drive decisions in the "Fast Loop." Shocks can alter the Dynamic Socio-Political state, creating incompatibilities with any exogenously defined contextual properties (such as a static SSP).

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across demographics, technology, institutions, and economics, not designed as waypoints on a continuous trajectory. Rather, the SRMP framework identifies that SRM-driven shocks can generate conditions *incompatible* with the SSP assumed at assessment outset. The framework does not prescribe how such incompatibilities should be operationalised; it establishes that ignoring them produces systematically incomplete risk assessment. How future modelling approaches might represent endogenous context evolution (whether through parameterised departures from baseline assumptions, branching scenario trees, or entirely novel architectures) is a research frontier we define, but do not resolve here.

5.2 Priority research domains

The SRMP framework identifies critical research gaps that must be addressed to enable robust representation of SRM risks and uncertainties. Present-day assessments must work with existing tools, which are limited in their ability to represent the full SRM risk space. We identify six priority domains:

- **Stochastic governance and geopolitical modeling.** Current models average over or omit fast-timescale human decision-making processes, particularly those involving governance failures, unilateral actions, and coalition dynamics. New assessment tools must explicitly simulate the "Fast Loop" (Figure 2), the rapid, event-driven decisions that generate termination shocks, counter-deployments, and escalation dynamics. This capability is essential for assessment of unintended consequences and represents the most critical modeling gap for SRM evaluation. Development approaches could include game-theoretic models (Pezzoli et al., 2023), agent-based frameworks, or stochastic decision modules, and analysis of how automated decision systems—if employed for real-time deployment control—might alter governance dynamics and introduce new escalation pathways.

- **Detection and attribution under natural variability.** Quantifying the irreducible uncertainty in detecting and attributing SRM effects amid natural climate variability is fundamental to uncertainty assessment. This requires systematic analysis of signal-to-noise ratios across deployment scales, patterns, and regions, including characterization of how misattribution (false positives or false negatives) could trigger governance responses. Such analysis must account for the asymmetry between global-mean signals and regional impacts, where detection challenges vary spatially and where internal variability can either mask actual SRM effects or falsely attribute unrelated events to the intervention.

- **Dynamic socio-political trajectory modeling.** Methods must be developed to operationalize the "Dynamic Context Loop" (Figure 2), enabling scenarios to represent how SRM-driven shocks can create incompatibilities with initially assumed contextual properties. This requires frameworks capable of representing endogenous departures from baseline governance, cooperation, or equity assumptions (through parameterised perturbations, branching scenario trees, or other approaches). Such capability is essential for assessment of long-term, path-dependent outcomes and for evaluating how SRM deployment might fundamentally alter the world's mitigation and adaptation trajectory.

- **Regional equity metrics and distributional analysis.** Frameworks to quantitatively assess "winners and losers" dynamics are critical for understanding how inequality feedbacks affect governance stability and adaptive capacity. This goes beyond static distributional analysis to model how perceptions of inequity feed back into the "Fast Loop," potentially triggering governance breakdown or deployment termination. Such analytical capabilities are necessary for evaluating SRMP-d (Free Driver) scenarios where coalition-optimized deployment explicitly creates regional disparities.

- **Ensemble-based probabilistic assessment.** The shift from deterministic optimal pathways to large ensemble simulations is necessary to characterize probability distributions of coupled human-climate outcomes under deep uncertainty. This requires developing efficient emulation strategies that enable exploration of the full SRMP parameter space across multiple SSP contexts and climate realizations. Such ensembles are essential for SRM risk characterization and for moving beyond "best-guess" scenarios to probabilistic risk assessment frameworks appropriate for low-probability, high-consequence events.

- **Economic frameworks for stochastic catastrophic risk.** New approaches are needed to evaluate interventions with low near-term costs but immense, deferred, stochastic liabilities (like termination shock) in ways that avoid inappropriate optimization under deep uncertainty. This may require alternatives to conventional cost-benefit optimization, such as robust decision-making frameworks (Weaver et al., 2013), minimax regret approaches (Hof et al., 2010), or resilience-based evaluation criteria (Feldmeyer et al., 2020). Economic assessment of SRM risks requires frameworks that can properly integrate event-driven, non-marginal risks rather than treating them as continuous probability distributions. These research priorities represent the minimum requirements to provide policy-relevant assessment of SRM risks beyond the idealized scenarios that dominate current literature.

Progress on these fronts would position the research community to fundamentally improve how SRM risks are evaluated in all future research and policy contexts.

6 Conclusions

Solar Radiation Modification (SRM) presents a fundamental challenge to existing climate assessment frameworks. Because SRM's sub-decadal climate effects couple directly to fast political and social dynamics, the simplifying assumptions that enable long-term GHG scenario modeling—averaging out stochastic shocks, treating socio-political context as exogenous—become untenable. Current tools, whether process-based IAMs or the SSP framework, are architecturally misaligned to this problem.

However, the troublesome omission of fast, stochastic, human-system shocks is not unique to SRM. Geopolitical conflicts, global pandemics, disruptive technological breakthroughs, and financial crises are also fast-term dynamics that our current models average out. The SSP framework community has already identified the need to account for such shocks and wildcards that could cause transformational change and shift a development pathway to a different SSP (O'Neill et al., 2020).

The SRMP framework developed here serves as a diagnostic tool that identifies *what must be represented* for adequate SRM assessment, and for any assessment of futures shaped by fast, stochastic, system-altering events. The "State vs. Driver" model and the three-loop architecture define the representational requirements that current frameworks fail to meet. But representation alone is insufficient. Even with rich characterisation of stochastic dynamics and context incompatibilities, a fundamental question remains: how should futures be *evaluated* when cost-optimization is inappropriate and deep uncertainty precludes probabilistic expected-value reasoning? The framework highlights the scope of what we cannot yet model; developing the decision-theoretic foundations to navigate these futures is an equally essential – and as yet unresolved – research frontier.

At its core, this paper confronts a profound epistemic challenge: the futures we most need to anticipate are precisely those that emerge from the irreducible entanglement of human behaviour, technological capacity, and physical systems – each deeply uncertain in isolation; their coupling produces not merely compounded uncertainty but genuine unpredictability – futures that cannot be assigned meaningful probabilities because the system's trajectory depends on decisions not yet made, technologies not yet deployed, and political configurations not yet formed. This is the condition of deep uncertainty, which implicitly applies to any attempt to project long-term climate futures.

Yet the prospect of SRM renders these issues unavoidable for any robust guidance. Unlike conventional mitigation, where multi-decadal climate response times provide a buffer against fast human-system dynamics, SRM collapses the timescales. Political decisions, technological failures, and climate responses all operate on commensurate speeds, creating tight feedback loops where misperception, miscalculation, or misfortune can rapidly generate divergent planetary trajectories. The difference between a world that emerges from a well-governed, time-limited deployment and one that suffers termination shocks, entrenched fossil dependence, or geopolitical fragmentation may hinge on unpredictable contingencies, and the consequences of these divergent paths could persist for centuries.

This is why naïve assessment built on idealised assumptions poses such acute risks at this juncture. If the research community evaluates SRM primarily through "best-case" scenarios – smooth deployment, perfect cooperation, orderly termination – it provides a systematically distorted evidence base for decisions that could prove irreversible. The architecture we have outlined here is not a solution to this problem; it is an attempt to highlight the scope of the risk assessment challenge. By naming the dynamics that must be represented – stochastic shocks, context incompatibilities, fast-loop feedbacks – we aim to establish minimum conditions for assessment that are able to represent the most damaging futures.

The intersection of volatile human agency, technological intervention, and Earth system process uncertainty may frustrate the kind of systematic analysis that policy processes have historically demanded for assessment of environmental questions. But the alternative, proceeding as if idealised models adequately characterise the risk space, is itself a choice with consequences. The SRMP framework is offered not as a map of the territory, but as an acknowledgment of how much territory remains uncharted, and how much depends on our willingness to confront that uncertainty honestly before decisions of planetary consequence are made.

Code availability. This is a conceptual paper; no code was developed for this study.

Data availability. This is a conceptual paper; no data were used in this study.

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