CLIMATE SECURITY AND SCALE: CLIMATE CHANGE RISK AND SECURITY AS AN ALL-SCALES, ALL-OF-SOCIETY CHALLENGE

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Dedication

I dedicate this to my wife, Marissa, and my two children, without whom none of this would have been possible.

Abstract

Climate security as an emerging field of study seeks to connect the substantial security-related challenges faced under climate change, and the ways in which climate change re-prioritizes issues at all scales of governance, and throughout all parts of society. This dissertation explores these perspectives to better understand how climate security differs from past approaches in security, and how climate change requires new paradigms to consider local, national, regional, and international assessments on risk and security. Through three papers, this dissertation assesses local approaches toward shifts in natural hazards through computational modeling, explores regional and global governance challenges that generate ethical and security concerns through attempts to mitigate climate impacts via geoengineering, and identifies current limitations on risk and security dialogues, particularly where conflict and disasters intertwine. The final paper also proposes a new conceptual model to advance approaches on assessing critical failure, the limits of mutual aid, and the assessment of "just securitization" when a referent of analysis faces significant impacts from disruptive events. This dissertation connects these issues of scale and dimensions of security to present climate security as a deeply interconnected and widely impacting issue that requires common framing and dialogues to prioritize capacity and understand limitations of future adaptation.

Keywords: climate security, climate change, natural hazards, arctic geoengineering, just securitization, security tipping points, risk analysis, climate governance.

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Chapter 1: General Introduction

1.1 Introduction

Unmitigated climate change is increasingly viewed as an existential risk to natural and social systems, but the effects of change are unlikely to be distributed evenly, whether spatially, temporally, socio-culturally, or hierarchically. These risks hold the potential for significant impacts, both directly and indirectly. The resulting amplification of these impacts creates security concerns at numerous scales, affecting local, regional, national, and global decision-making. This dissertation approaches these concerns through three articles, focusing on the geophysical implications of climate change, the potential for ethical and security concerns resulting from human attempts to mitigate warming, and through the need for common terminology and framing of security and risk. All three articles are connected through dimensions of security and risk and are guided by theories in international relations and disaster studies, to bring closer alignment between these fields and the interlinked complexities generated by climate change.

An examination of persistent themes offers a prelude to the articles in this dissertation. Climate change as a growing concern has emerged through a process of scientification, politicization, and increasingly securitization, escalating the level of importance at all scales. But there remains a question of how we unify these scales, to promote a common dialogue, and offer translation between these levels when it comes to issues of climate security. This dissertation explores these issues from perspectives of international security, disaster studies, and model impact chains, and aims to address this critical gap. Thus, the goal of this dissertation is to answer the question, "How do perspectives on climate security guide a shared understanding of all-scales, all-of-society risk?"

World leaders,[1–4] institutions, and the general public[5] have increasingly identified climate change as one of the greatest challenges modern humans have ever had to face. Some have gone so far as to label it an existential threat,[6] and a growing body of knowledge identifies it as an existential risk to human civilization.[7] The perception and acceptance of this existential threat or risk have evolved over time, from something that was once considered a non-priority to the view that human civilization itself is potentially in danger due to these changes which require significant actions to address them. This has followed from the understanding of natural processes involved in climate change, which led to greater capabilities in identifying the potential for future change.

As greater understanding of natural implications grew, the resulting implications for human and social systems have followed.

More recently, the Intergovernmental Panel on Climate Change's (IPCC's) Sixth Assessment Report (AR6) identified the vast potential for ecosystem and human impacts in future decades, across a range of scenarios, from local degradation of natural environments, to mass migration and the potential for inter-regional conflict.[8] In the United States, the Fifth National Climate Assessment similarly presented concerns ranging from food security to national security, identifying risks to "defense, diplomacy, and development agencies," with national security implications rated as very likely, with a high level of confidence.[9] In 2023, U.S. President Biden proclaimed that the "only existential threat humanity faces even more frightening than a — than a nuclear war – is global warming going above 1.5 degrees in the next 20 — 10 years."[10]

The framing of the issue has been the topic of much discourse, at local, national, and international levels of analysis. Work focused on the origins and contributing factors of climate change continues, but increasingly focuses on finer aspects, as major drivers have been clearly identified. Efforts at the societal level are shifting toward attempts at both mitigating the causal factors, but also adapting to the expected changes, as it becomes apparent that emissions are unlikely to be abated prior to significant impacts being realized.[8] Studies in 2024 indicate that the planet may have already marked the first crossing of the 1.5°C increase from the pre-industrial baseline (1850-1900) that the Paris Agreement identifies as a key threshold to prevent major impacts.[11] Some of the related risks are being escalated in priority due to the substantial impacts they pose to humans and governments.

Concerns around the impacts of climate change are increasingly being framed as issues of other forms of security, with dimensions of these impacts connecting to food security, health security, environmental security, human security, national security, and others. The overt prioritization of these security-related issues, or escalation beyond the normal political process, can be seen through frameworks on *securitization theory*, which helps to explore the process by which a particular issue is moved from the non-political or political into the realm of security which may justify extreme measures to combat the perceived existential threats.[12] This approach emerged from the broadening of security beyond the military and the political, as well as the deepening of security beyond the national level toward individual and global perspectives.

The prioritization of climate issues varies substantially by region, by levels of governance, and by the available resources or capacity a particular group may have to address such challenges. This subjective framing of issues plays into the challenges of climate change mitigation, adaptation, and security, and is a critical part in understanding the capacity within or resilience of systems to resist climate-related impacts. This approach also helps to inform key sections of this dissertation, not only presenting climate security as an all-scales, all-levels challenge, but by providing foundational mechanisms to flexibly analyze those issues across those dimensions. Prior to exploring the individual chapters of this dissertation, however, a brief overview of the emergence of climate security will be provided, as well as a summary of key issues relating to both physical scale and governance scale, as they relate to the work.

1.2 Dimensions of Climate Security

The origins of the term *climate security* are closely linked with the emergence of environmental security, with links between them identified as early as 1987, when "Our Common Future" (sometimes referred to as the Brundtland Report) was released by the UN World Commission on Environment and Development.[13] While the report did not mention climate security as a self-contained phrase, it highlighted climate as being directly linked with issues of environmental security. The same report helped popularize ideas of sustainable development, linking environmental climate systems and human development, and helped form the foundation for the UN Sustainable Development initiatives.[14] Exploration of the concept continued throughout the 1990s, as the broadening and widening of security expanded into environmental,[12] human,[15] and other dimensions of security, while climate research gained in prominence. Direct mentions of climate security emerged amidst these debates,[16] and while often framed within human security or environmental security contexts,[17] connections to the potential for conflict, migration, and interstate threats were specifically highlighted by the late 1990s.[18]

Over time, climate security itself emerged as a more clear conceptualization of security related challenges that stem from climate change drivers, as the United Nations identified linkages between climate, energy, and security,[19] and individual nations began to identify connections to national security concerns when it was recognized that "climate change and energy will play significant roles in the future security environment."[20] Driven by these wide-ranging and shifting perspectives, climate security is often applied in a broad and context flexible way, to many different scales (both physical and social), referents (people, objects, ideals, etc.), and often with different motivations. As with the term *security* itself, climate security has come to be viewed through many lenses and priorities and is heavily context dependent.[21]

1.3 Issues of Scale

The measures taken to address climate insecurity are deeply connected to issues of scale, both in physical and social dimensions. While the understanding of physical systems has advanced substantially in recent decades through advanced research on natural systems and in the development of models to identify and assess future impacts from potential climate change pathways,[8,22] the decision-making realm faces a regularly and rapidly changing array of competing interests and drivers that may interfere with the ability to mitigate climate impacts cohesively, where national security interests often compete with those at the individual or human level. The intersection of both physical environmental systems and the decision-making realm therefore needs to account for issues of scale in the natural and social worlds.

Proactive, predictive planning and capacity building for environmental change and climate security heavily depend on an understanding of the scale of processes, observational data, models, and uncertainty. General Circulation Models (GCMs) offer a computational approach for assessing climate shifts,[23] primarily in the form of understanding of global challenges at coarse scales to assess general warming trends, precipitation, and other variables based on possible futures dependent on human decision-making efforts. While these models provide an overall understanding of global energy balances and climate shifts, they may not adequately capture or address the factors affecting local scales. Therefore, it requires added processes and scientific expertise to translate global model impacts to local scales.

An increasing number of models and methods exist to take global model projections to local scales and help to increase the spatial resolution of data to address local or regional planning concerns. This includes the downscaling of global data to finer resolutions, as well as the inclusion of more localized processes, such as regional or local hazards, to provide more specific spatial planning information to decision-makers. At these more localized levels, it also allows for accurate spatial awareness of specific hazards and vulnerabilities. However, this process of shifting global projections to local scales holds significant uncertainty, leading to challenges in implementing solutions confidently at the local level, when assessing the cost-benefit tradeoffs of any proactive measures.

At the local level, climate change is often viewed as a risk modifier, increasing the potential for local hazards, altering land planning requirements, and altering the known landscape, bringing with it new and potentially unseen events. From this perspective, climate security is often framed as a threat to *human security*.[15] From the human security perspective, threats and hazards are generally assessed from the perspective of people-centric views, or the human impacts from a threat, and while difficult to define, are presented as a negative concept, in that insecurity is more easily defined than security.[15] In the realm of military and national security, climate change has been identified as a "threat multiplier" since at least 2007, when the term was coined.[24] Prior to that, the idea was that climate change was viewed primarily "as an environmental issue, not a security concern."[25] Over time, threats to nation-states from climate change have been more clearly identified,[26] whether in terms of operational capacity, the generation of conflict through natural resource depletion (e.g., water, food, etc.), and concerns over increased mass-migration due to inhospitable conditions (e.g., heat waves, droughts, floods).[6]

Complicating factors further is that due to the widespread impacts of climate change, it can be difficult to unify an understanding of how human behavior, combined with natural hazards, may combine to present complex or compounding risks to humans. Efforts to unify these security concepts began with advancing the understanding of hazards as components of securitization.[27] This was further refined, to present two paths under securitization, as threatification and riskification, which address the broader range of risks.[28] This terminology helps to bridge the gaps between international and local, as well as the origin of the risk, whether human-caused or natural.

As opposed to many traditional security-related issues, climate security is present at all scales and social levels of analysis, from the global, to the national, local, and individual. Emissions from various Greenhouse Gases (GHGs) may originate from local sources, but the sum of their outcome produces significant global change, including warming oceans, loss of polar and terrestrial ice, and changes to atmospheric conditions which ignore nation-state boundaries. Changes are not evenly distributed, however, leading to disproportionate shifts in natural hazard occurrences and, as a result, unequal impacts to affected populations.

From the *levels of analysis* perspective, global governance structures struggle with obtaining agreements that require national level implementation or local level execution of plans. While the Paris Agreement was a significant step forward in policy-driven attempts to curb emissions, nations have had mixed levels of success in mitigating those emissions and competing global security concerns have disrupted the proposed timelines. A failure to meet the 1.5°C global temperature rise is expected to result in high-risk global changes, such as those mentioned above, with a projected increase of droughts, coastal flooding, and "risks to health, livelihoods, food security, water supply, human security, and economic growth."[29] Recent reports indicate "global emissions are not in line with modeled global mitigation pathways consistent with the temperature goal of the Paris Agreement."[30]

At the nation-state level, governments have struggled with meeting the aspirational goals identified in the Paris agreement, as competing security priorities have limited the ability of many to focus heavily on GHG reductions. It is important to note that intentions toward climate policy are not always a clear indicator of the level of commitment to carrying out those goals over time.[31] International conflicts, such as the escalation of the Ukraine-Russia War since early 2022,[32] force a restructuring of those priorities, and have substantial impacts on national and global energy priorities.[33] While conflicts often tend to generate substantial emissions, this particular conflict has highlighted the need for energy independence and security at a national level, with nations looking to establish national level supplies and internal capacity, generating a reduction in efficiency and higher total consumption. Some analysts have gone so far as to indicate that the war's effects have led nations to believe that "energy independence is now seen as a precondition to political security."[34]

At the sub-national level, local governments and subunit level actors may have some influence over the broader climate mitigation, through voluntary or regulatory practices, but increasingly at this level, actors are left facing the burdens of global system changes. Natural hazards are often localized issues, requiring local scales of decision-making, planning, and adaptation to avoid the greatest impacts. However, many locations are now facing greater impacts than previously, and shifting hazards that had not been previously faced. This puts an immense burden on the local levels of governance to adapt to problems far outside of their control.

Finally, at the individual level, people face the greatest risks and challenges, with the least control over those risks. Individuals are affected by disasters, economic challenges, health concerns, food security, and many other factors because of climate insecurity, and this can be compounded by external global events, creating heightened risks at all levels. Returning to the Russia-Ukraine war, the indirect impacts of the conflict led to not only national priorities on energy but significant increases in energy prices at the household level.[35] Further impacts are escalated, as de-riskification efforts by insurance companies and re-insurers are leading individuals to bear the brunt of risks when it comes to home insurance in identified high-risk areas, as insurers seek to minimize losses.

At each of these levels, decision-makers have different levels of control over the impacts of climate security and related systems. While the individual may have substantial control over their own energy consumption practices, they have little control over global consumption levels or markets. At the global level, UN agreements depend on the ability of nation-states to implement and adhere to climate mitigation efforts. All of this depends on the shifting priorities nations face, as regional conflicts, migrations, economic pressures, energy concerns, and other security related threats force a constant reprioritization of resources. When faced with threats seen as far off into the future, national and local leaders may be pressured into focusing on the more immediate concerns. Having established the importance of climate security at scale, a brief overview of the papers that form the core of this dissertation will be provided, before expanding on those efforts.

1.4 Three Perspectives on Climate Security

This dissertation focuses on three perspectives regarding climate security, to include local-scale issue identification and planning through riverine extreme events, regional scale issues of security and governance through evaluation of geoengineering efforts in the Arctic, and an "all-scales" approach toward identifying potential systemic failure points in a security referent, as well as potential risks to the survival of that referent. While hazards and threats are often treated as separate incidents when it comes to emergency management, disaster studies, and international security, the nature of climate security necessitates a unified approach toward assessing risk. Therefore, the studies presented here explore both the threat and hazard perspectives of risk, both in isolation and from a more unified perspective, to include not only realized or actual events, but perceived and potential events, allowing for the exploration of plausible futures. Since climate-related hazards have the potential to amplify threat likelihood and impact, and vice versa, approaching from a more holistic perspective will be necessary if planners and security analysts are to be able to assess total risk and impacts from a climate security perspective.

1.4.1 Interior Alaska Hydrological Extremes

The first paper (which is provided as Chapter 2 of this dissertation), "Chapter 2: Modeling of Future Streamflow Hazards in Interior Alaska River Systems and Implications for Applied

Planning,"[36] utilizes a computational hazard modeling approach to identify risk in a local ecosystem, by exploring Interior Alaska river basins and the potential shifts that may occur under future climate conditions. Using dynamically downscaled climate data produced at the Alaska Climate Adaptation Science Center (AKCASC), for both historical (2008-2017) and projected (2038-2047, 2068-2077) time periods, model simulations were developed and run for each period using the WRF-Hydro model,[37] a hydrology modeling environment designed to operate in a flexible, operational, or research environment. This study explores a heavily natural hazards driven approach, while contextualizing the history and related built infrastructure systems that may affect uncertainty and pose challenges in decision-making.

This research emerged from collaborative efforts between two projects, including the Strategic Environmental Research and Development Program (SERDP) funded RWO 227: Aquatic Ecosystem Vulnerability to Fire and Climate Change in Alaskan Boreal Forests, and the National Oceanic and Atmospheric Administration (NOAA) project Experimental Framework for Testing the National Water Model: Operationalizing the Use of Snow Remote Sensing in Alaska. The goal of the SERDP project was to explore future land management challenges faced in fish and wildlife habitats managed by the Department of Defense when faced with shifts in fire and flood behavior, with a heavy emphasis on hydrology modeling and monitoring. The NOAA project was focused on the exploration of operationalizing the WRF-Hydro model in regions of Alaska, and greater understanding of snow influences in the region. The overlap of these projects provided significant opportunities for collaboration.

Through regular discussions and work sessions, both projects gained from the expertise of team members, and the utility of the models and datasets involved, allowing for significant progress to be made toward both efforts. This author was primarily funded by the SERDP project for this work, but participating as an unfunded collaborator on the NOAA project provided significant insights that greatly benefited the work involved. This paper, at the time of this dissertation, is currently unpublished, but prepared with the intent to submit to an already identified special issue journal on extreme events in hydrology and was written by this author with insights and guidance provided by the proposed co-authors, Vladimir A. Alexeev and Peter A. Bieniek, throughout the project.

This local hazard assessment perspective highlights the challenges in modeling and uncertainty faced in an area that is highly susceptible to climate change and rapid state change due to the thawing of local sporadic and discontinuous permafrost in the region, changes to precipitation patterns from regional forcings, and the difficulties of performing local hazard mapping and planning under high uncertainty. This effort also helps to emphasize the local scale of climate change related work, as individuals, cities, municipalities, and other local governments struggle to identify adaptation measures for existing hazards that may be substantially different in the future, as well as the potential to face those which may have never been seen in the region (in terms of frequency, severity, or duration). Additionally, while not covered within the chapter, the perception and prioritization of particular hazards offers insights into the dimensions of security that may be prioritized at the community level.

1.4.2 Arctic Geoengineering

The second paper (which is Chapter 3 of this dissertation), "Arctic Sea Ice Decline and Geoengineering Solutions - Cascading Security and Ethical Considerations,"[38] evolved from discussions among the co-authors, in preparation for participation in the Circling the Arctic conference, held by the Center for Ethics and the Rule of Law (CERL) in October 2020.[39] Following the conference, continued research explored the potential for escalation toward conflict, security concerns, or ethical challenges related to events that stem from geoengineering or climate engineering approaches in the Arctic. The emphasis looks at the use of engineering-based solutions to reduce regional or global impacts as something that has been proposed as a more plausible route to rapidly limit warming, as a result of growing skepticism over the ability of successful reduction of global emissions.

Driven by a perception of inaction in international policy, a growing sense of urgency is leading to the rapid growth of efforts to develop, test, and implement geoengineering measures that could radically alter future warming pathways. This urgency highlights the pathways toward securitization, as actors begin to explore extreme measures to combat potentially catastrophic impacts of climate change. However, such urgency has also raised a range of concerns for local populations and ecosystems, as well as the potential for unintended consequences like political or armed conflict that may be associated with attempts to heavily manage the atmosphere, ocean, and land interfaces through solar radiation management, carbon recapture, or thermal engineering. This paper explores the potential consequences of these changes from the perspective of securitization theory, risk governance, and inclusive governance to highlight the less explored risks associated with geoengineering in the realm of governance and conflict, rather than solely geophysical concerns. It then goes on to propose mechanisms based on existing structures that may help reduce these risks proactively.

The resulting paper was primarily developed and written by the author of this dissertation, while sections 2 and 4 were initially led by the co-authors, Uma S. Bhatt and Troy J. Bouffard, respectively, then integrated and refined by this author. The final paper was published in 2022 in *Challenges* and has resulted in multiple collaboration opportunities post-publishing. The paper itself prompted an invited Arctic Research Consortium of the United States (ARCUS) seminar lecture for the Arctic Research Seminar Series, with a wide range of attendees.[40] The lecture, as well as the paper, also resulted in an invitation to join the International Arctic Science Committee (IASC) workshops on geoengineering in the Arctic in 2024.[41] These continuing workshops and efforts endeavor to explore issues of feasibility, ethics, and other concerns as they relate to the growing areas of interest around geoengineering solutions. The paper and subsequent involvement has led to numerous contacts and discussions from interested researchers, as well as private organizations exploring these themes.

1.4.3 Security Tipping Points

The third paper (provided as Chapter 4 of this dissertation), "Security Tipping Points: A Measure of Securitization,"[42] was developed to address what was identified by this author as a critical gap between security and disaster studies. Inspired by work on one of the field papers completed as part of comprehensive exams for this doctoral program, a currently unpublished paper titled "The Convergence of Disaster Risk Studies & The Emergence of Disaster Risk Reduction," as well as emerging global events, to include the invasion of Ukraine and various natural disasters throughout the COVID-19 pandemic, it became apparent that there was a vital need for common frameworks that addressed an all-scales approach toward risk and security dialogues. This effort therefore works to advance the understanding of semi-objective securitization-based approaches toward risk assessment.

Security discourse has long been framed as both objective and subjective, where threats or risks are constructed by security actors. However, the need to discern between subjective and objective threats, as outlined in Chapter 4, guides the proposed conceptual model, which aims to provide a more cohesive approach toward assessing when a threat to the survival of a referent is within the range of legitimate possibility. With the complexity of climate risks affecting human, national, and other forms of security, it is necessary to be able to address these risks within a unified framework, and the conceptual model outlined assists both the security analyst and the disaster manager in understanding where tipping points exist that may endanger the stability of the system or referent in need of protection. It also helps to explore and explain the perspective of political actors working to securitize issues, whether for "just" purposes, or in contrast with claimed just purposes. With the expectation that climate change challenges will be faced by all levels of society, and most likely by every society on Earth, it will be necessary to manage the available resources and focus on threats and hazards that are likely to pose significant dangers. This framework helps to assist in that endeavor, to understand where stability may exist, and where it may need reinforced, across governance, temporal and spatial scales.

This paper was developed and written by this author and involved discussions and feedback from committee members and colleagues. While initially focused on merging specific forms of security theories, eventually it was recognized that a more security agnostic approach was required, which leans on securitization theory, but is not bound to it. The intention is that, while this paper is directed at an international security audience, it will have broader utility across fields, offering common dialogues and conceptual frameworks to assess risk in a scale-flexible way, with unified terminology between international security, disaster and risks studies, and related fields. This paper is currently prepared for publication in a journal with a background in securitization theory and constructivist approaches to international security, with intention that publication efforts will follow shortly after the completion of this doctoral program.

1.5 Summary of Themes

Together, these papers emphasize a focus in this dissertation on the critical need for multi-scalar, multi-disciplinary approaches to explore climate security related challenges by integrating hazard assessment, security and ethical implications, and consequence analysis of climate change as well as responses, across multiple levels and scales of analysis. The complexity of these issues demands a holistic, integrated approach that spans disciplines and scales. To achieve that goal, this work leans heavily on lessons in securitization to identify both the process by which issues of security may emerge across sectors and levels under climate change, as well as the challenges of addressing these issues in competing and complementary ways. While the work in this dissertation does not intend to propose normative solutions to these problems directly, it aims to offer another perspective on evaluating these problems that allows for a more nuanced and holistic exploration of those problems. Identifying the potential for local hazards through hydrological modeling, connecting adaptation measures to the complexity of socio-cultural systems, and employing approaches toward an all-scales framework for assessment of critical failure points helps to advance the understanding of climate security, while providing an applied direction to a common understanding of risks to survival. The following papers each advance important aspects of this overall goal.

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Chapter 2: Modeling of Future Streamflow Hazards in Interior Alaska River Systems and Implications for Applied Planning

2.1 Abstract

There is a growing need for proactive planning for natural hazards in a changing climate. Computational modeling of climate hazards provides an opportunity to inform planning, particularly in areas approaching ecosystem state changes, such as Interior Alaska, where future hazards may differ significantly from historical events. This paper considers improved modeling approaches from a physical process perspective and contextualizes the results within the complexities and limitations of hazard planning efforts. Therefore, the aim is not only to improve the understanding of potential climate impacts on streamflow within this region, but also to further explore the steps needed to evaluate local scale hazards from global drivers and the potential challenges that may be present. This study used dynamically downscaled climate forcing data from ERA-Interim reanalysis datasets and projected climate scenarios from two General Circulation Models under a single Representative Concentration Pathway (8.5), to simulate an observational gage-calibrated WRF-Hydro model to assess shifts in streamflow and flooding potential in three Interior Alaska rivers for a historical period (2008-2017) and two future periods (2038-2047 and 2068-2077). Outputs were assessed for seasonality, streamflow, extreme events, and comparison between existing flood control infrastructure in the region. Results indicate that streamflow in this region is likely to experience increases in seasonal length and baseflow, while the potential for extreme events and variable short term streamflow behavior is likely to increase, leading to increased water management requirements. Results are contextualized based on regional impacts, basin specific changes, and potential for long-term decision-making.

Keywords: climate change, extreme events, risk modeling, dynamical downscaling, natural hazards, climate adaptation

2.2 Introduction

There is a growing need for proactive approaches towards planning for natural hazards under changing climate. River systems in Interior Alaska are currently undergoing significant changes, which have the potential to amplify under a changing climate in the future. Warming temperatures, combined with increased precipitation, have been shown to increase permafrost thaw within the region[1,2] and hold the potential for rapid subsurface warming and the decline of the region's near-surface permafrost.[3,4] As permafrost rich environments experience a complex relationship with subsurface hydrology in this region, understanding how these systems are likely to be altered in the future is critical for river and ecosystem management, risk identification, and long-term planning for the built environment. In areas lacking significant observational records, historical calibration is challenging, therefore the confidence in future projected changes may reduce the ability to confidently engage in no-regret adaptation or mitigation measures.

Approaches to assess peak streamflow, particularly in remote locations, may involve a wide range of methods including modeling, as well as observed discharge measurements and remote sensing.[5–7] Prior studies indicate that annual and peak streamflow among Interior Alaska rivers has declined in recent decades, particularly in snowmelt-dominated systems, although minimum baseflow has increased in winter months.[8] Increased minimum baseflow has been closely linked with warming temperatures in the region, late fall precipitation increases, and altered season lengths, leading to deepening of the active layer and increased groundwater flow.[9,10] Studies also indicate that the region is expected to continue to experience increases in precipitation into the future,[11] leading to greater uncertainty of the system under future projected climate. Since most planning efforts are based on historical occurrences, significant ecosystem state changes can present unexpected challenges, to include amplification of existing hazards, or the introduction of new hazards. The intent of this paper serves two primary purposes: 1) to enhance and improve model simulation approaches from a physical process perspective and 2) contextualize modeling results within the complexities and limitations of hazard planning efforts.

In this study, three Interior Alaska river systems are simulated using the WRF-Hydro modeling environment,[12] to assess the potential future trajectories of mean and extreme streamflow using downscaled data from multiple climate models for a single future emissions scenario. These models were selected as part of a previous assessment of general circulation model (GCM) performance within Arctic Alaska and Canada.[13] Based on the results of these modeling efforts, the impacts are assessed in terms of policy and decision-making uncertainty and the limitations that may be associated with high uncertainty with regards to long-term climate adaptation measures. Therefore, the aim is not only to improve the understanding of potential climate impacts on streamflow within this region but also to characterize the steps needed to explore local scale hazards from global model outputs and the potential challenges associated with those steps.

2.3 Background

2.3.1 Study Area

Our study area is situated in Interior Alaska and includes the Chena (5740 km^2), Salcha (5350 km^2), and Goodpaster (1770 km^2) River basins (see Figure 2.1).[8,14] These three basins flow into the Tanana River (66,205 km^2),[8] a major tributary of the Yukon River system (853,300 km^2), which eventually flows into the Yukon-Kuskokwim River Delta and exits into the Bering Sea.[15] All three basins are currently in areas with a high presence of discontinuous permafrost, where thawing has the potential to alter groundwater flow.[15] Local ecosystems consist primarily of subarctic boreal forest with coniferous dominant vegetation,[16] which is undergoing a shift toward a deciduous dominated area, driven by warming temperatures and wildfire activity.[17]

The climate is categorized as subarctic, with annual temperatures in the region ranging from very cold, dropping below -40 °F (-40 °C) in wintertime, to very warm, often exceeding 80 °F (26 °C) in summertime.[18] Temperatures have trended up in the last few decades[19] and are expected to continue to rise in the future, with both minimum and maximum temperatures shifting upward.[11] Historically, precipitation in the region is typically low, with annual means in low-lying areas below 300 mm in the Fairbanks area,[15] while areas at higher elevations within the study area may exceed 700 mm accumulation annually.[20] The 2020 census indicates that approximately 100,000 people live in the study area, with the vast majority located in the Chena River basin downstream of and protected by the Chena Flood Control Project in and around Fairbanks and North Pole, Alaska (see Figure 2.1), with as many as 85,000 people at risk from a catastrophic failure of control measures.[21,22]

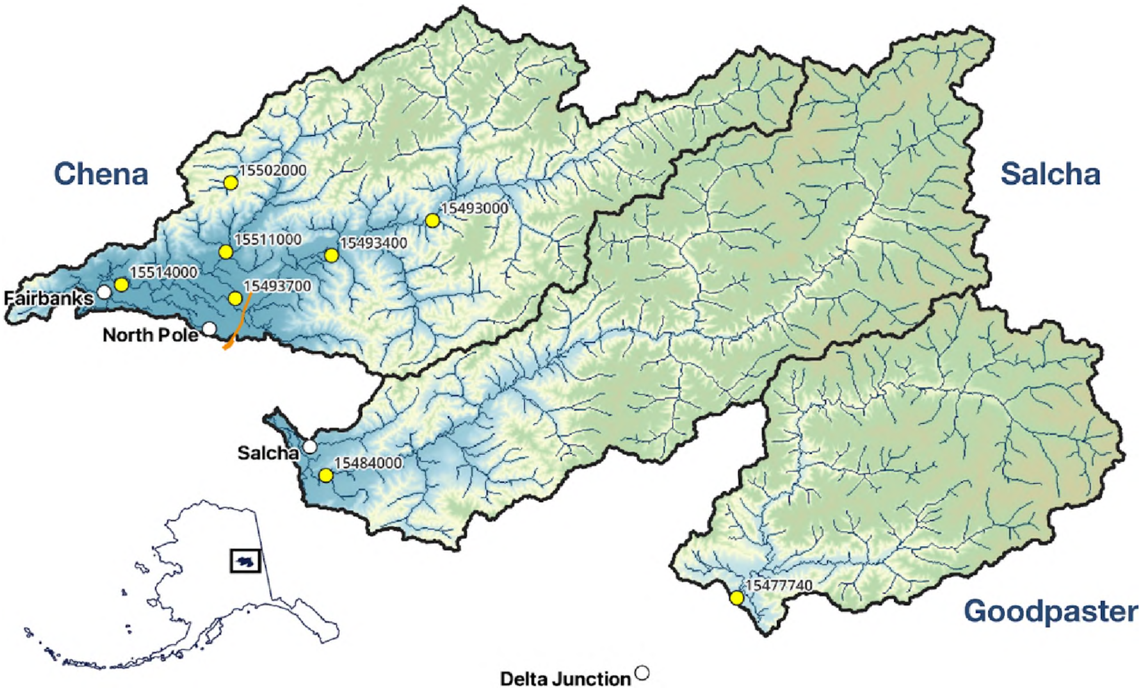

Figure 2.1: Map showing the three primary study areas.

Chena (top left), Salcha (middle), Goodpaster (bottom right) River basins. Gage locations are shown with yellow dots and their gage ID. Communities within the region are indicated with white dots. The orange line, near North Pole, Alaska, represents the extent of the Moose Creek Dam and Chena Flood Control project, including the reservoir and spillway into the Tanana River. Original Alaska IFSAR 5 m digital terrain model (DTM) is shown as base layer in green to blue gradient.[23] The inset map shows the State of Alaska, with the location of the study areas shown within a black rectangle.

2.3.2 Flood Control and Flood Events

The Chena and Salcha Rivers have significant influences on the nearby communities of Fairbanks, North Pole, and Salcha, Alaska. These river basins each have a history of generating flooding events throughout the region. Notably, the Fairbanks area was the location of an extreme flooding event in August of 1967, which resulted in \$85 million in damages at the time,[24] or over \$775 million adjusted for inflation (calculated in August 2023).[25] During the 1967 event, approximately 95 percent of the city of Fairbanks was flooded, with some areas being inundated with nearly 5 feet of water.[24] During the 1967 event, some streamflow gages in the region were completely destroyed, limiting the ability to collect data related to the flood.[24] This event prompted substantial changes to the management of local river flows, directly leading to the construction of the Chena Flood Control Project and the Moose Creek Dam, which was intended to divert water during high flow events.[26] Shortly after the completion of the flood control project, increased instrumentation and monitoring efforts were established to assess the operational capabilities and impacts of the system on the local environment.[27]

Since its installation in 1979 and first activation in 1981,[28] the Chena Flood Control Project has been activated 30 times (as of 2021) to prevent downstream flooding impacts.[29] The project is designed to manage peak streamflow such that downstream flow is limited to approximately 12,000 ft^3/s (340 m^3/s) through Fairbanks, based on its assessed channel capacity.[30] If the system reaches this capacity, the flood gates at the dam are lowered to divert excess flow into a connected reservoir. In an event where this reservoir capacity is exceeded, overflow is diverted into the Tanana River through a spillway past the Tanana Levee.[22] As of 2024, the flood control project is undergoing modifications and upgrades as part of a U.S. Army Corps of Engineers project to improve streamflow management and reinforce the embankment.[31] These upgrades are expected to be completed in 2026.[32] This effort also reduces the potential for seepage under the main levee through the inclusion of deeper groundwater barriers.[22,31] Activation of the flood control system also impacts sediment accretion upstream of the dam and a reduction of nutrients downstream, which presents a series of challenges for flood diversion and wildlife within the area. While this flood control project primarily affects only one of the three study basins, it protects most of the population in the study area and therefore has a significant impact on human safety and the overall protection of the built environment of the region.

Flooding events in the Chena River basin typically fall under two primary patterns: spring snowmelt and intense summer rains.[28] Historically, the majority of these appear as summertime rain events, primarily occurring in June, July, and August, during short duration, intense precipitation events.[28,33] The 1967 flood, for example, generated nearly 10 inches of precipitation within a 12 day period in August,[24] which approaches the total annual average for the area. The duration of the activation of the flood control project has varied substantially across events, with the longest event taking place in 1992 spanning 19 days and resulting in the only time excess flow poured into the Tanana via the spillway.[34] This event was unusual as it combined a heavy winter snowpack, late spring snowmelt, and intense rains.

Flooding events in this region can also be caused by ice-jams. Ice-jam occurrence is often a mix of hydro-meteorological conditions combined with stream morphology characteristics, such as sinuosity.[35] For instance, in 2020, the Chena Flood Control Project was activated due to a spring ice-jam event, which is seen as a semi-unique event in the history of the project, only having happened one other time, in 2002.[36] However, in the Salcha River basin, the history of ice-jam flooding is more prevalent, with a number of events occurring in recent decades during spring breakup.[37] Streamflow rates in the Salcha River tend to peak at higher levels, despite having a similar overall extent as the Chena basin system (5740 km2 for the Salcha basin, versus 5350 km^2 for the Chena basin), potentially leading to more ice jam effects.[8] During the 1967 floods, the Salcha River experienced intense flooding events, and while preventative removal of the gage at the time limited data gathering, manual measurements were later used to generate peak flow estimates of nearly 97,000 ft^3/s (~2,750 m^3/s).[24] Flooding in 2008 near Salcha was recorded as the most significant event since the 1967 event, with over 100 homes experiencing flooding.[38] Since 2012, as part of a railroad expansion project, an installed levee has helped to reduce risks associated with spring melt and river breakup events on the Salcha.[39,40]

While the Goodpaster River basin is significantly smaller than either the Chena or Salcha River basins, it has a higher proportion of its catchment area located above 600 m in elevation, compared to the other study basins.[14] With no major settlements along the Goodpaster, floods have a less direct impact on populations, but its inclusion offers an additional unmanaged river system for comparative analysis.

2.3.3 Streamflow Gages

Within the study area, the U.S. Geological Service (USGS) maintains multiple official streamflow gages, with six located in the Chena River basin, one in the Salcha River basin, and one in the Goodpaster River basin.[41] For consistency, the use of the USGS preferred spelling of gage, rather than gauge, is used within this paper.[42] The placement of these gages and their record lengths play an important role in the calibration and analysis potential within this study.

The record-length of most existing gages in the Chena River basin is limited when it comes to long-term historical as well as pre-dammed flow. The streamflow gage with the longest record is located downstream of the Chena Flood Control Project, near Fairbanks (15514000, Figure 2.1). However, since the completion of the flood control project in 1979,[28] the downstream record reflects a managed environment with the goal of preventing or minimizing flooding. Thus, any study of peak streamflow events must be compared to unmanaged areas along the river systems.

The nearest upriver gage from the flood control project, Chena River Below Hunts Creek (15493400),[43] was installed in 1989 and has operated nearly continuously since. Peak flow measurements from this gage align closely with peak flows from the upriver gage at Chena River near Two Rivers (15493000), with KGE scores of 0.84, and it would be reasonable to assume within the same basin system that flow patterns downstream would similarly be reflected under a natural or unmanaged flow environment. The focus on the Chena River Below Hunts Creek gage (15493400) allows for calibration as the furthest downstream point that is not under active management of streamflow, providing closer comparisons to natural flow. Additional gages in the Salcha and Goodpaster River basins are used as secondary analysis sites, despite having a shorter observational record.

2.3.4 Discontinuous and Sporadic Permafrost

Permafrost plays a significant role in ground hydrology, acting as both a barrier to downward infiltration, as well as a cause of rapid degradation or alteration of previously existing groundwater and surface water patterns. Wildfires, warming, and heavy precipitation events can modify permafrost extent and features, resulting in changes to subsurface flow dynamics that may generate permanent changes to existing streamflow patterns and local ecosystems.[44] In some cases, permafrost degradation can occur rapidly, through short term extreme events.[45] In Interior Alaska, there is a significant presence of sporadic and discontinuous permafrost,[46] which presents additional interactions for streamflow due to its susceptibility to rapid thaw events, altering subsurface hydrology.[1] Warming temperatures, combined with greater snow cover, have already been attributed to increases in active layer thickness in the region and increases in permafrost temperatures in the last few decades.[47] Most recently, between 2017 and 2019, there have been numerous examples of sites within the region where the permafrost has not completely refrozen in winter, generating suprapermafrost taliks, or patches of ground that are unfrozen but sit above the permafrost and below the active layer.[47] In the future, permafrost thaw models indicate a substantial decline in sporadic and discontinuous permafrost within Interior Alaska, which is likely to impact seasonal runoff patterns, as soil storage capabilities and ground connectivity increase due to a reduction in ground ice.[4]

2.3.5 Hazard Assessment

As with many regions, the rivers of Interior Alaska are an important part of the natural ecosystem and play an integral role in the built environment of populations living within proximity to riverine ecosystems. This role is deeply connected to flooding events, which act as potential hazards to the population, as well as infrastructure (e.g., roads, airports, houses). Traditionally, flood hazards have often been assessed based on a recurrence interval (e.g., 1 in 100 years, 1 in 10 years, etc.), sometimes referred to as a return period. These intervals are normally derived from known historical occurrences and sometimes an extrapolated probability distribution based on those occurrences and may be represented as something like $T_r = 1/P$, where T_r represents a return period, and P represents the annual exceedance probability at a certain threshold.[48] Inverting this approach offers an annual exceedance probability (AEP), which provides the percent chance of the event occurring annually (e.g., 1-percent per year, 10-percent per year, etc.).[49] The 1-percent AEP has been used by the United States National Flood Insurance Program since the 1960s as the basis for the insurance program.[50] These thresholds help to determine insurance rates for those living within flood prone areas but may lack nuance when it comes to the variability of specific events, which vary in intensity, duration, and frequency and may have high spatial variability.[51]

The approach to defining flood hazards focuses on an assumption of stationarity in flood recurrence causes. However, it is increasingly being recognized that non-stationarity of flood recurrence and other hazards may make it difficult to use this approach in the future, as system state changes lead to entirely new hazard regimes.[52] In areas where climate change is expected to produce events that significantly depart from known event probabilities, it becomes important to consider extreme events under a range of possible future conditions to better understand the ability of existing systems to withstand those extremes. Emerging extreme events, which may not have been experienced in the past within a given region, present additional challenges for local planners and residents, as it may require significant study to proactively mitigate the associated hazards, and introduces new uncertainties.[53] However, perceptions of risk are often counterintuitive, as indicated by recent surveys highlighting that those living in high flood risk areas may hold lower levels of risk perception surrounding those events.[54] Perception of risk is also often influenced by multiple factors, with awareness of risk being only one of many components, while preparedness against a particular risk and levels of worry or stress about those particular risks also influence their prioritization.[55]

2.4 Methods

The WRF-Hydro model, which offers an open-source flexible and extensible modeling architecture was selected as the primary modeling tool for simulating streamflow in this study.[56,57] WRF-Hydro includes a land-surface module, overland routing, channel routing, and supports the ability to couple directly with WRF atmospheric models, or to run in standalone mode, which is the approach used within this study. WRF-Hydro was selected both due to its basis as part of the National Water Model,[58] as well as to act as a testbed for Interior Alaska basins. While WRF-Hydro has seen limited applications in Alaska, it was adapted for the region during the study period and is now in limited operational use in some regions of the state.[59] While WRF-Hydro has been widely tested in the contiguous 48 states, differences in Alaskan ecosystems, including subsurface dynamics, seasonal cycles, and local infrastructure, required modifications to the study region.

Substantial experimentation, both in the initialization and setup of the model, was required to correctly account for permafrost through frozen ground modules. Additional effort was also required to identify and develop datasets that would correctly represent regional hydrologic behavior, particularly in areas with active flood control structures, due to their influence in rerouting streamflow. Input data sets required to run the WRF-Hydro model included topography and climate forcing data.

The WRF model was used to dynamically downscale climate data to force and calibrate WRF-Hydro, following similar prior work at 20-km,[60] taking reanalysis and GCM data from coarse scales to produce high resolution (1 km) air temperature at 2 m, precipitation, specific humidity, wind, radiative forcing, and surface pressure. To adjust for over representation of precipitation in the dynamically downscaled WRF model outputs, the future climate forcings were biased corrected using Quantile Delta Mapping (QDM) approaches, which allows for the preservation of relative changes.[61] Calibration of the model focused on comparison of the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim data to key streamflow gage locations and overlapping periods between reanalysis and projected data.[62] Analysis of WRF-Hydro model output data was performed using python based geospatial and analysis libraries, leveraging matplotlib,[63] numpy,[64] pandas,[65] and xarray,[66] to summarize and visualize model outputs.

2.4.1 Model Setup

WRF-Hydro simulations were developed under version 5.1.1 of the model.[12] Simulations were run using Weather Research and Forecasting (WRF),[67] downscaled data for the ERA-Interim reanalysis dataset,[62] and two climate models selected from the Intergovernmental Panel for Climate Change (IPCC) Coupled Model Intercomparison Project (CMIP) phase 5,[68] to include the Community Climate System Model (CCSM) version 4 from the National Center for Atmospheric Research (NCAR),[69] and Climate Model version 3 (CM3) from the Geophysical Fluid Dynamics

Laboratory (GFDL).[70] Both models were run using their outputs from Representative Concentration Pathway (RCP) 8.5.[71] Both CCSM and GFDL were run for three time periods (2008-2017, 2038-2047, and 2068-2077), while ERA-Interim was run for 2001-2018, to include the overlap period between the two GCMs. Each run used the parameterized landscape setup from the output of the calibration results as the starting point, described later in this section, offering direct comparisons in time spans between reanalysis and modeled data sets. Simulations were performed using overland flow and gridded diffusive wave routing, at an hourly time step, for the entire simulation period, for each of the six periods plus historical. As discussed in the domain setup, model resolution for reach characteristics were set at 250 m, while WRF forcing data was at a resolution of 1 km.

2.4.2 Domain Setup

As portions of the study domain represent managed waterways, it was necessary to develop a domain that properly reflected flood control structures in the area (levees, dams, etc.) that may alter the flow of water differently than a natural flow regime. Thus, we adjusted the flow and routing layers using the WRF-Hydro preprocessing tools.[72] Early efforts, using default digital elevation model (DEM) layers, led to overflow between the two basin systems. This occurred primarily due to coarse DEMs (90 m) failing to effectively capture the widths of those flood control structures, resulting in unexpected overflow events between basins. This result also offered an unexpected highlight to the importance of the existing control structures, and the potential for spillover should those systems fail, and natural flow were restored.

Routing paths and basin extents were generated programmatically using the WRF-Hydro pre-processing tools for the National Center for Atmospheric Research (NCAR),[72] with the Alaska IFSAR dataset using the digital terrain model (DTM) acting as the primary DEM layer for the domain, which covers the entire study domain at a 5 m resolution.[23] The DTM was chosen to best represent the direct flow surface for routing, which largely excludes the heights of vegetation, which may inadvertently affect routing. IFSAR was then upscaled to 250 m for computational efficiency during simulations. Different minimum basin stream size values were tested, and a final value of 100 cells was used in the routing to identify streams, to strike a balance between accuracy and computational efficiency.

The total area of the domain was established to include three main basin systems: the Chena, Goodpaster, and Salcha (see Figure 2.1). The primary comparative locations for forecast points are identified as USGS gage 15493400 (Chena, below Hunts Creek), 15484000 (Salcha, near Salchaket), 15477740 (Goodpaster, near Big Delta). These locations represent gaged locations for each basin that are not subject to flow restrictions from flood control measures, allowing for analysis of natural flow regimes. Lakes and reservoirs were not included as part of this work, as the primary emphasis was focused on extreme events and scouring that occurs during high flow. However, the resolution of the DTM does support these efforts in the future.

For each actively maintained USGS gage location, however, a forecast point was identified within the routing in order to provide analysis and comparisons. In addition to observation sites, an extra forecast point was added to each basin to gather total outflow from each of the basins. Manual correction of gage locations was applied in cases where gages were not perfectly aligned with identified reach segments within the model, to align forecast points with the nearest available gage reach segment.

2.4.3 Forcing Data

The forcing data in this set of simulations was produced as part of a larger project, focused on the modeling of Interior Alaska river systems, in order to identify implications for ecosystem management and impacts to fish populations within the study domain.[73] As high resolution forcing data for the study area was previously unavailable, the development of these data sets was necessary. Historical and future forcing data was developed through dynamical-downscaling within WRF of the ERA-Interim historical reanalysis data set, as well as projected climate data for RCP 8.5 of the GFDL and CCSM models.

The dynamical downscaling approach applied in this study was based on work previously performed for statewide Alaska downscaling efforts,[60] and existing tools and expertise were leveraged to produce a 1 km resolution product centered on the study region, based on the bounding box visible in Figure 2.1. For the new 1 km downscaling product, no spectral nudging was used and the cloud microphysics scheme was adjusted after visually comparing the precipitation outputs with historical radar observations for a summer test period. Testing using a nested domain revealed that the primary impact on the downscaled outputs was primarily on the spatial distribution of summer precipitation, with minimal differences in the winter. For this study, a single 1 km resolution domain was used to limit the computational requirements of the downscaling.

The downscaled WRF runs were conducted for 54-hour periods that included a 6-hour spin-up that was discarded, producing successive 2-day runs spanning each simulation period. Snow depth from the end of each prior 2-day simulation was used to initialize the next simulation period to provide a temporally consistent, high-resolution snowpack. Post downscaling, WRF outputs were adjusted to align with the WRF-Hydro model input requirements, such that hourly accumulation of precipitation was converted to precipitation rates in mm/s.

2.4.4 Bias Correction

Initially, uncorrected simulation runs of the future projected models (CCSM and GFDL) had significant precipitation biases which resulted in a high number of extreme events over the observed period. These issues appeared to originate within the dynamically downscaled outputs, inherited from the GCMs and ERA-Interim data, indicating that all of these datasets produced higher rates of precipitation in the region, although to varying degrees, when compared to PRISM precipitation baseline data,[74] as seen in Figure 2.2. This uncorrected set of model runs produced both historical and future simulations that far exceeded historical flow rates, making it challenging to properly assess change over time. However, analysis of the high precipitation bias in these models aligns with previous work assessing coarser downscaling efforts in the region, indicating that both CCSM and GFDL projections appear to produce wetter than expected conditions over the observed period within the study region.[60] Based on this early evaluation, it was determined that bias correction approaches would be necessary to accurately represent precipitation for the study region and to be able to identify decadal shifts more clearly.

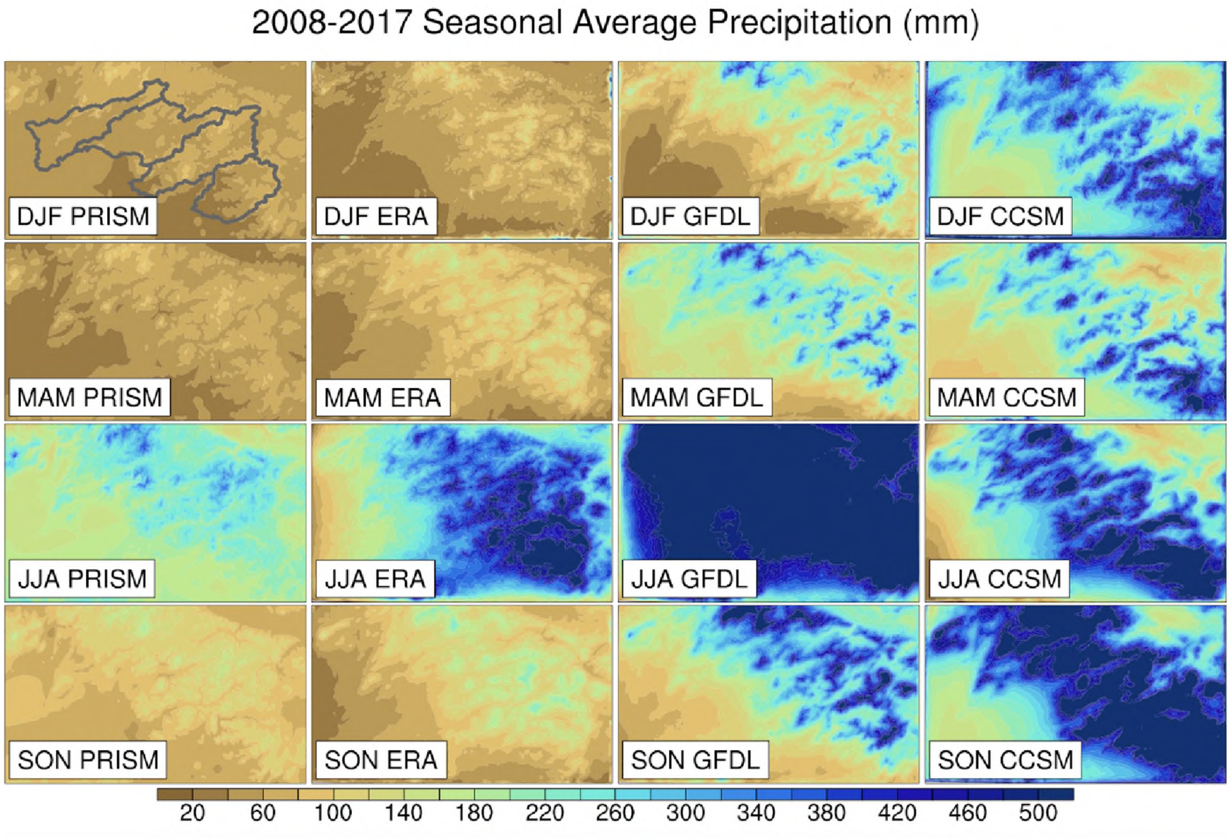

Figure 2.2: Precipitation Bias

Comparison of three-month groupings of seasonal bias over the study area, comparing PRISM as the baseline, with ERA-Interim, and RCP 8.5 for GFDL and CCSM.

For the needs of this study, the xclim package, which provides numerous built-in bias correction and indicator tools, was used to bias correct the downscaled data sets for GCMs, both for historical and future time periods.[75] QDM was selected as the training and adjustment method in order to better preserve extreme events within future datasets, as it has been shown to increase the ability to represent and maintain peak flow events.[61]

Precipitation data was bias corrected through multiplicative scaling to retain the intermittent nature of precipitation in the region, while temperature data was corrected via an additive application of deltas. Data was corrected using a monthly grouping, with 2008-2017 ERA-Interim data used for the reference data set and the 2008-2017 period used as the historical period for each GCM. Biases were calculated using the full month and then applied to temperature and precipitation within the modeled time periods (2008-2017, 2038-2047 and 2068-2077). Attempts were made to use larger quantile sets (50 instead of the default 20), but this resulted in amplified extremes within the observed overlap period and was discontinued.

Comparisons between pre- and post-bias corrected datasets were assessed during the overlap period, to evaluate GCM improvements against ERA-Interim baseline data. Bias corrected temperatures followed similar annual and seasonal patterns for both CCSM and GFDL. Precipitation data varied more significantly between models and decades, with annual variability remaining higher in CCSM in future decades, while GFDL presented a more general upward progression of precipitation as decades advanced (see Figure 2.3). CCSM produces seasonal behavior including steeper monthly average precipitation increases, but the total annual precipitation rises to higher maximums in GFDL, exceeding 700mm annually (Figure 2.3).

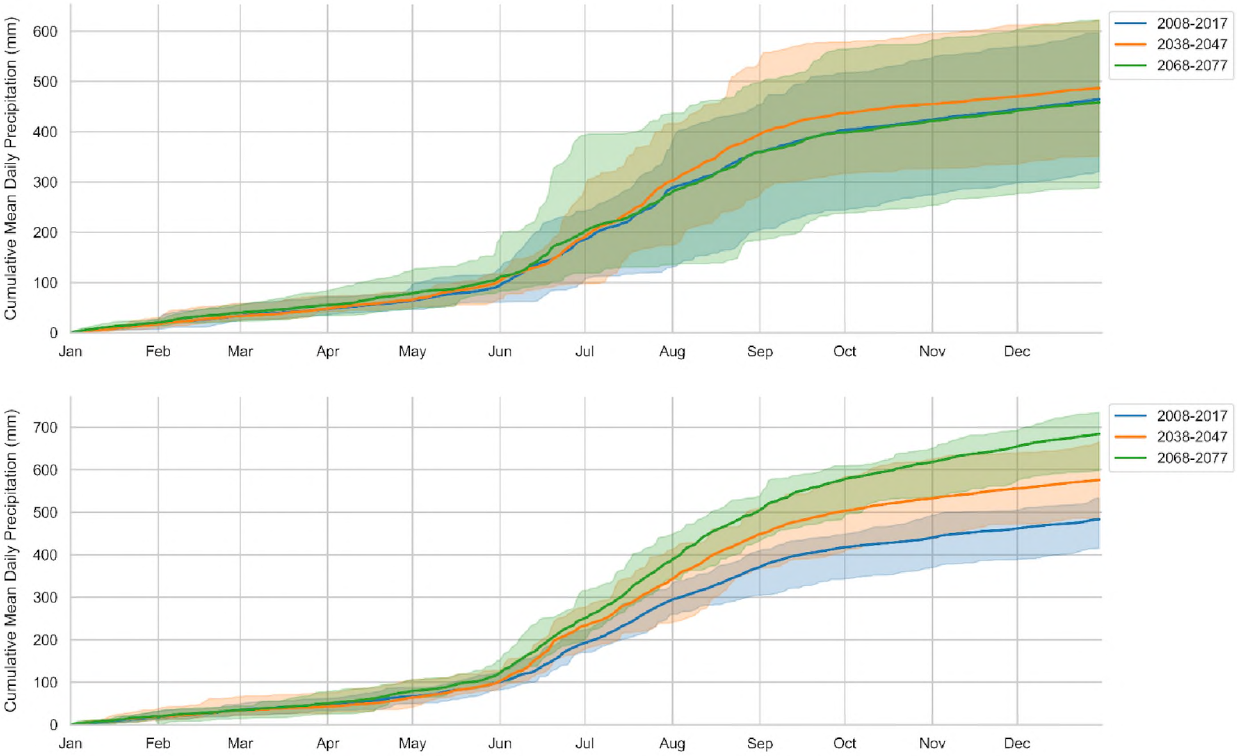

Figure 2.3: Model precipitation

Bias corrected mean cumulative annual precipitation data for the full domain, CCSM (top), and GFDL (bottom). Bands represent annual minimums and maximums for each time period.

2.4.5 Calibration

The WRF-Hydro model was calibrated using PyWrfHydroCalib,[76] an internal parameter sensitivity and analysis package written in python and R, which is developed and maintained by NCAR. This package makes use of the R package hydroGOF (to perform goodness-of-fit testing) behind a series of controller scripts to streamline the calibration process across basins, and to manage spin-up, calibration, and validation phases.[77] This allowed for a semi-autonomous, minimally supervised, and time-reduced calibration of WRF-Hydro domains and streamflow, based on selected metrics, and was designed to allow for a high number of subdomains to be calibrated across major basins. This toolset was originally developed to assist NCAR in the calibration of basins throughout the contiguous United States as part of the National Water Model[58] and has been tested across thousands of basins in the contiguous United States.

For this study, as replicating peak flow events was the primary goal, Kling-Gupta Efficiency (KGE) was selected as the best available calibration within selected toolsets, as it has been shown to have improved effectiveness at replicating peak flow events, while reducing loss of other parameter performance.[78] While scores above certain thresholds may be considered good for KGE, this depends on the aim of the modeling efforts.[79] In this case, since semi-automated fit testing was performed, scores were used to inform points of diminishing returns, not as a specific threshold for success. WRF-Hydro was calibrated in two distinct batches, based on available computational resources, with the first beginning with default initial conditions for 250 iterations. The spin-up phase was run for 2001-2010 to establish baseline soil parameters and frozen ground, while the calibration phase was focused on 2013-2015, both to account for high flow events that occurred during that period as well as to balance computational efficiency.[33] The validation phase was then set for 2016-2018, to test calibration performance for each iteration.

The first round of calibration produced a maximum KGE score of 0.71, while the average of all runs was 0.60. Generally, KGE is said to perform satisfactorily above 0.5. The highest performing set of parameters produced were then used as starting conditions for a second, 200 iteration run, and produced a maximum KGE score of 0.72, with an average across all runs of 0.61. The final highest performing run was used to establish the baseline for climate simulations and future projection based runs. The negligible improvements of the second batch of runs indicated diminishing returns that did not justify further rounds. The calibrated model was re-run through an extended reanalysis period within the ERA-Interim based forcing data, to provide comparisons for 2001-2018.

2.5 Results

2.5.1 Calibration Results

Using the derived model calibration parameters produced simulated maximum streamflow values comparable with observed streamflow peaks for the Chena River but led to poorer performance within the Salcha River, where maximums exceed observed events (Figure 2.4 and 2.5). Both seasonal streamflow distributions and peak flows for the Salcha River indicated more substantial mismatches between observed and modeled data, despite being one basin adjacent to the Chena River, where calibration was primarily focused. Surprisingly, for the Salcha, streamflow was simulated with improved skill for two years (2009 and 2017), even though they were not part of the calibration years. However, the performance was still degraded when compared to the Chena. This may be improved upon in future studies through the refinements of components such as the subsurface soil properties, frozen ground conditions, and vegetation layers and most importantly by basin-specific calibration. Comparisons between the observed and simulated data can be seen in Figures 2.4 and 2.5. The wet-bias in the model forcing data (as seen in Figure 2.2) is present in the WRF downscaled ERA-Interim data as well as GCM outputs when compared to PRISM. While attempts were made to avoid overfitting during calibration, this bias persists in projections as well, since calibration was based on the ERA-Interim reanalysis data, rather than correcting to PRISM.

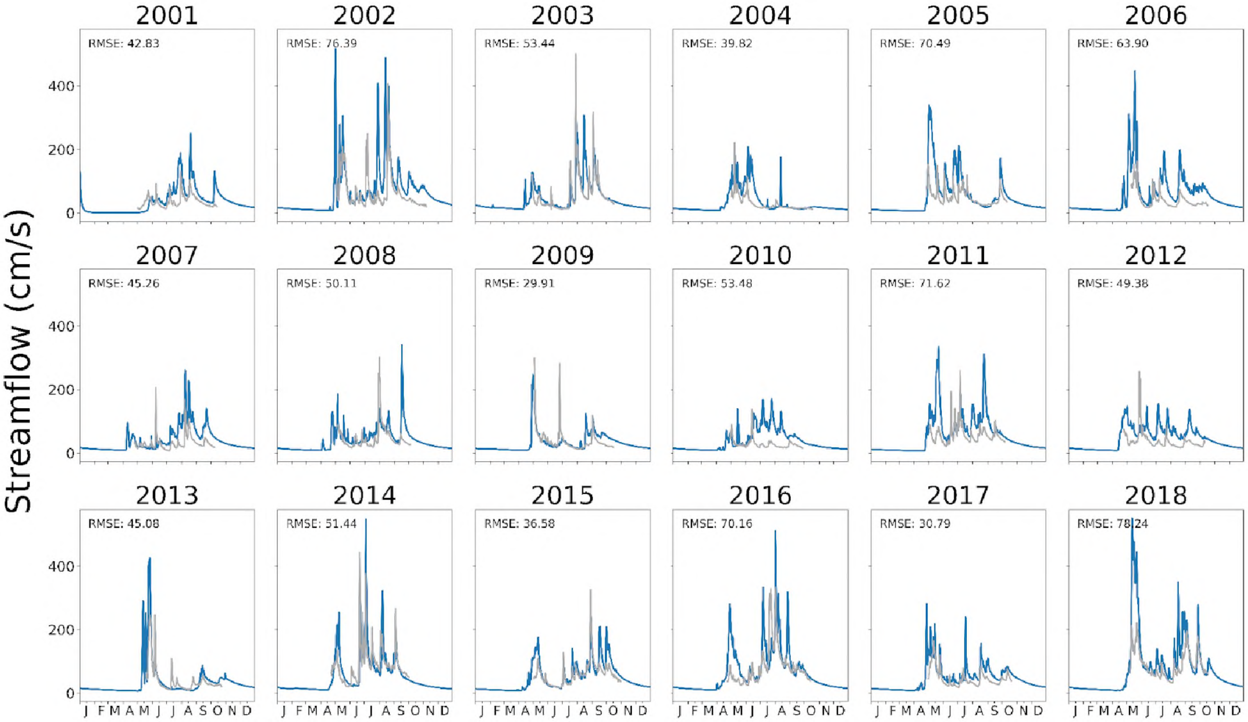

Figure 2.4: Calibration Results of Chena River

Comparison of observed gage data (gray) at Gage ID 15493400 (Chena Below Hunts Creek) with simulated model runs (blue) for the 2001-2018 period, Jan - Dec, following calibration.

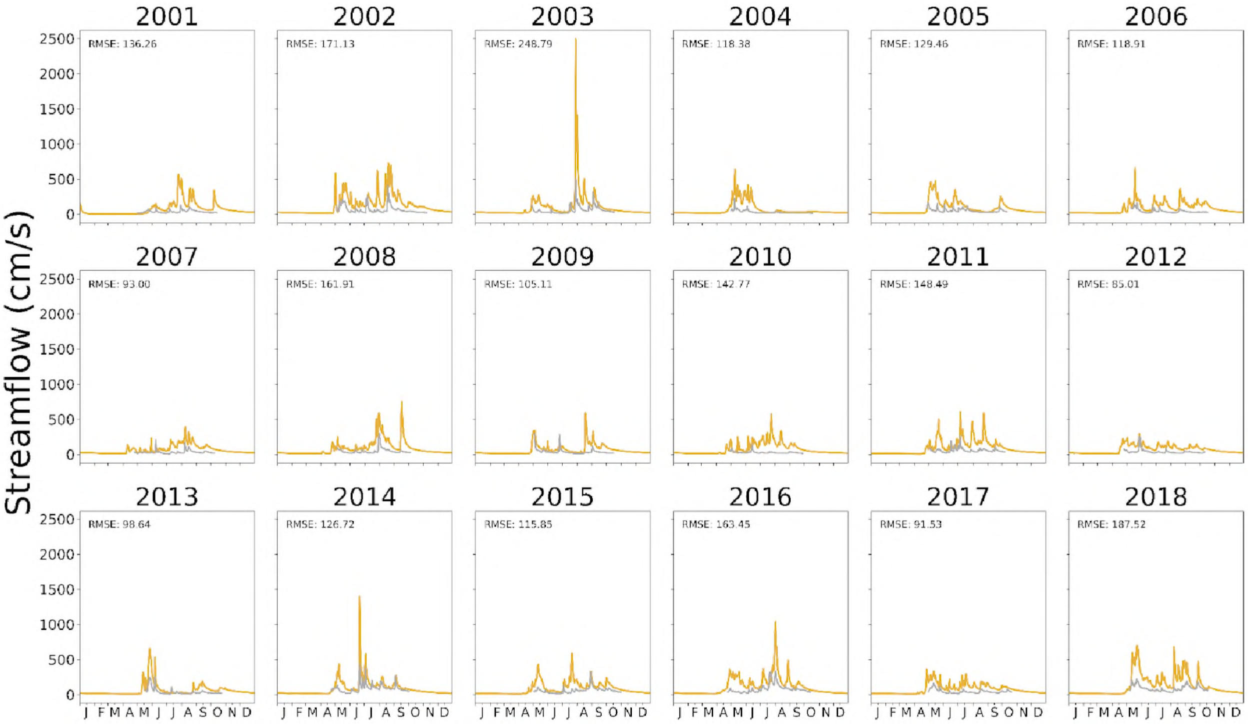

Figure 2.5: Calibration Results for Salcha River

Comparison of observed gage data (gray) at Gage ID 15484000 (Salcha) with simulated model runs (gold) for the 2001-2018 period, Jan - Dec, following calibration.

2.5.2 Model Divergence

The divergence between future GCM-driven simulations presents itself in the distribution of both extreme events and in non-extreme streamflow. This divergence can be seen in Figures 2.6, 2.7, and 2.8. For these plots, the box represents the interquartile range of annual means or maximums, while whiskers represent the high and low within variance from the quartiles. Outliers are marked with circles. GFDL shows a clear increase in mean annual streamflow and total streamflow when compared to the historical period, as well as an increase in extreme flow events (see Figure 2.6). Variability tended to be significantly lower within GFDL as opposed to CCSM and produced consistently higher streamflow across basins, in some cases producing a two-fold increase in streamflow over the duration of simulated years, particularly in mean annual flow. This is consistent with precipitation patterns identified earlier, with GFDL experiencing decadal increases in annual precipitation. While GFDL generally maintains a narrower range of variability in most decades and basins, the 2038-2047 period within the Goodpaster River basin produces particularly high variability, which narrows significantly by the 2068-2077 period (Figure 2.8).

CCSM presents a modest downward trend in long-term streamflow relative to the historical period, indicating declines in mean annual streamflow, total annual streamflow, and widening variability in annual maximums when compared to the historical values (Figure 2.6, 2.7, and 2.8). This pattern presented similarly across the basins. However, the Salcha experienced higher variability in maximum streamflow events compared to the other two basins, particularly during the observed period (2008-2017), when extreme streamflow events in CCSM nearly doubled those generated by ERA-Interim simulations (Figure 2.7). In future decades, a relative decline in maximum streamflow is observed, while GFDL experiences outliers (e.g. extremes) late into the 21st century.

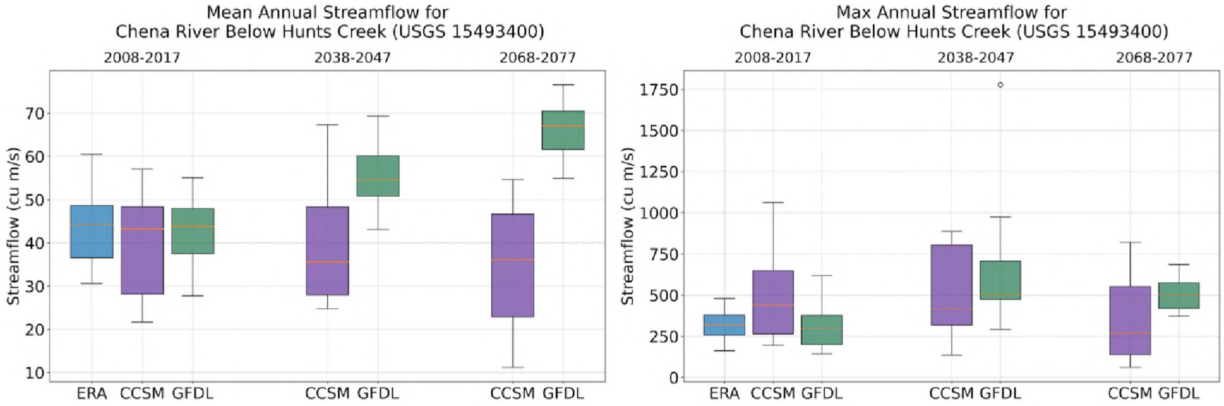

Figure 2.6: Mean and max flow for Chena River basin

Annual mean flow (left) and maximum flow (right), for location of USGS Gage 15493400 (Chena River, Below Hunts Creek), for the observed period (blue), and projected CCSM (purple) and GFDL (green) simulations.

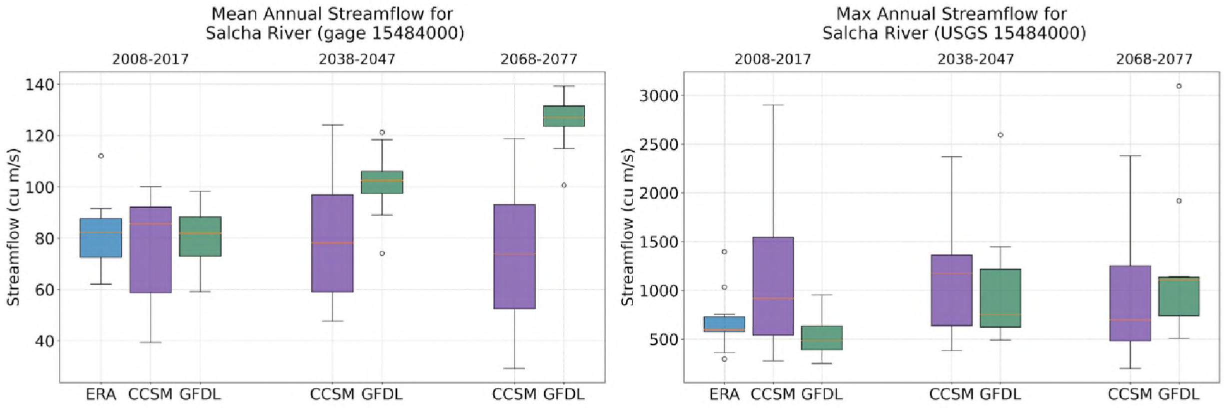

Figure 2.7: Mean and max flow for Salcha River basin

Annual mean flow (left) and maximum flow (right), for the location of USGS Gage 15484000 (Salcha River), for the observed period (blue), and projected CCSM (purple) and GFDL (green) simulations.

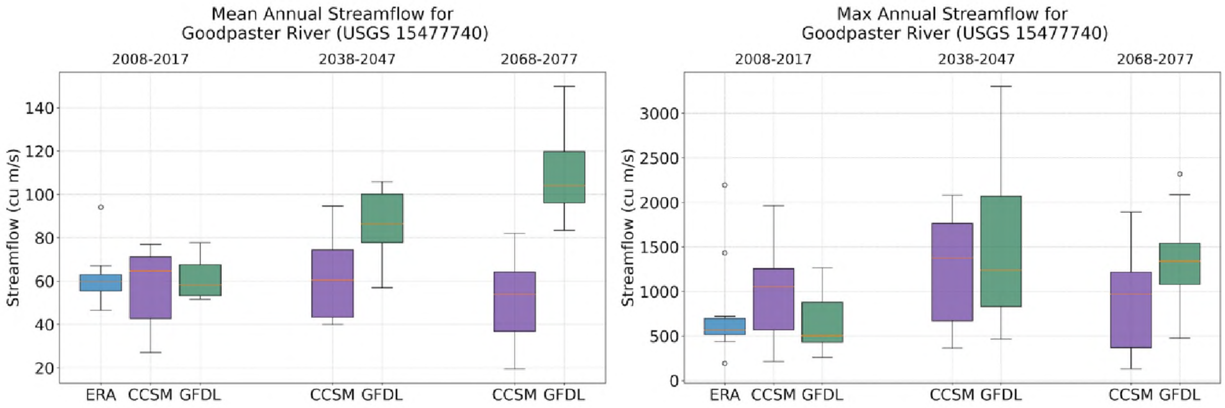

Figure 2.8: Mean and max flow for Goodpaster River basin

Annual mean flow (left) and maximum flow (right), for the location of USGS Gage 15477740 (Goodpaster River), for the observed period (blue), and projected CCSM (purple) and GFDL (green) model runs.

2.5.3 Seasonality

Based on temperature trends in the region, and previously mentioned expectations of multi-seasonal warming, the results indicate a lengthening of the streamflow season, with earlier snowmelt events, and higher flow events extending later into the warm season. These seasonal expansions can be seen in Figure 2.9, where snowmelt-driven streamflow events occur one month earlier, in April instead of May. Rainfall driven events during late summer experience an increase in magnitude over earlier decades. In the case of GFDL, the result is a more bi-modal pattern of streamflow increase with both spring and late summer high flow patterns. CCSM, however, experiences a significant increase in mid-summer streamflow, particularly in the 2038-2047 period, driven by multiple years of high precipitation (as seen in Figure 2.3).

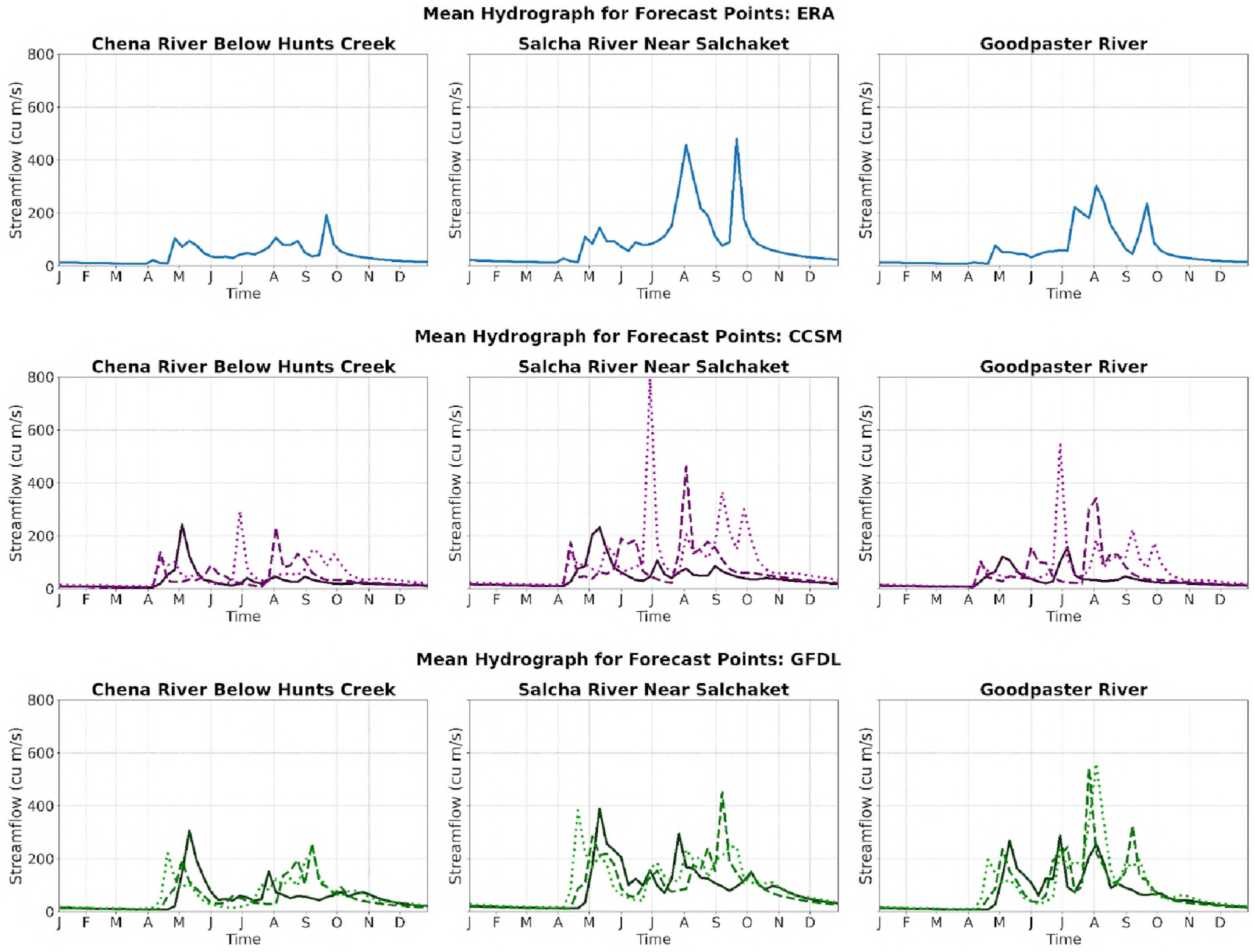

Figure 2.9: Mean weekly streamflow averaged by decade

Mean weekly streamflow hydrograph by decade comparison for ERA (top, blue), CCSM (middle, purple shades) and GFDL (bottom, green shades) during the 2008-2017 (dark solid line), 2038-2047 (medium dashed line), and 2068-2077 (light dotted line) time frames, for the Chena River Below Hunts Creek, Salcha River near Salchaket, and Goodpaster River gage location.

2.5.4 Flood Control Implications

Based on the previously estimated 12,000 ft^3/s (340 m^3/s) threshold used to restrict downstream flow rates, the frequency of activations of the flood control project in the future increases significantly under GFDL, with over twice as many events in the mid-decade period, and over four times as many events in the later decade, while flood frequency appears to stay within a similar range under CCSM. While CCSM highlights a relative increase in the 2038-2047 period followed by a decline, GFDL indicates a consistent increase in both the duration and frequency of flood events. Particularly under GFDL, these results indicate that flood control management may be required more frequently in the future, with an increased number and longer activations of the flood gates. Previous activations of the Moose Creek Dam have highlighted the potential for nearby residences and area to experience groundwater infiltration, as the dam is unlined and subject to hydrostatic pressure transfer. Newer renovation projects may help to reduce, but not eliminate these challenges, and may be tested under the extremes indicated for GFDL.[22]

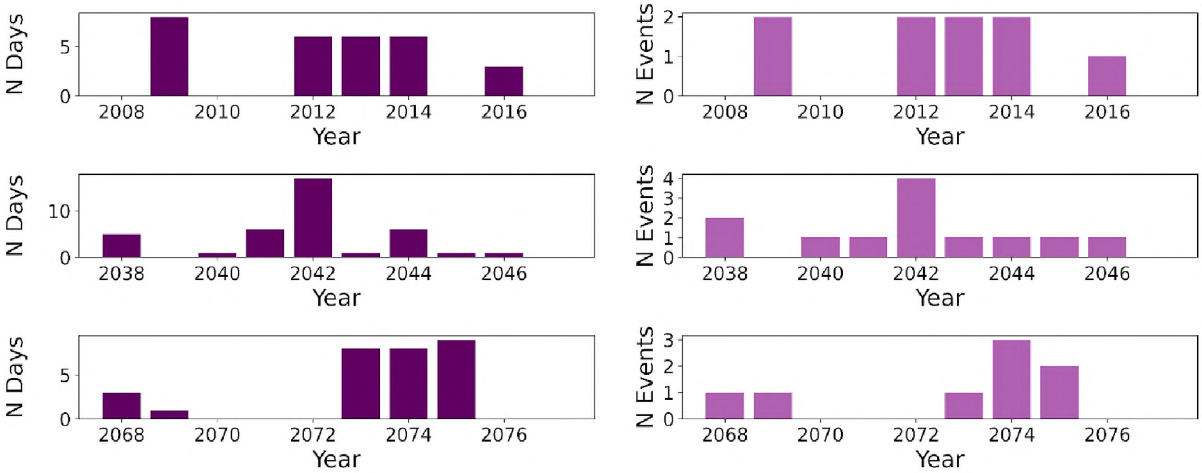

Figure 2.10: Flooding Events for CCSM

Events modeled under CCSM indicating crossing of pre-established flood control thresholds. Dark purple represents the Number of Days where streamflow rates exceeded the 12,000 ft^3/s (340 m^3/s) threshold. Light purple represents the total Number of Events per year exceeding that rate. Each event represents one or more days where the streamflow continuously exceeded thresholds.

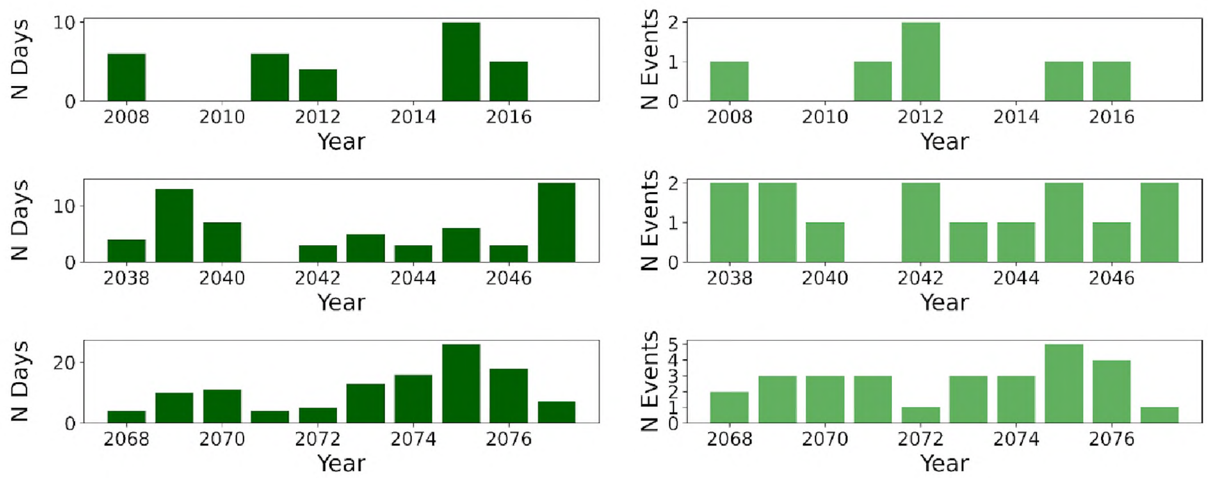

Figure 2.11: Flooding Events for GFDL model

Events modeled under GFDL indicating crossing of pre-established flood control thresholds. Dark green represents the number of days where streamflow rates exceeded the 12,000 ft^3/s (340 m^3/s) threshold. Light green represents the total number of events per year exceeding that rate. Each event represents one or more days where the streamflow continuously exceeded thresholds.

2.6 Discussion

This study highlights a number of important factors when it comes to the behavior of future streamflow within the study area, emphasizing the potential for future projections to improve our understanding of Arctic riverine systems in terms of shifts of seasonality, the intensity of extreme events, and changes to mean annual streamflow within river systems. Shifts in infrastructure demands and the need for mitigating controls are also important factors that present opportunities for decision-makers to plan around system changes well in advance of those changes being realized. This allows for a potential reduction of impacts through proactive adaptation, whether through nature-based solutions (e.g., establishment of non-buildable floodable lands),[80] or engineering guided development (e.g., dams and levees).[81] Other approaches aimed at risk-reduction are also possible, including rezoning to reduce new risk, or buyouts within existing high-risk areas.[82]

The results of this work show variability within streamflow and system response patterns in future simulations under RCP 8.5 for the two models considered (GFDL and CCSM). Based on the results, the seasonality of future streamflow is expected to lengthen in the future, leading to earlier snowmelt events in the spring, and later streamflow events in the late fall. This impact is primarily influenced by the extension of warm seasons, where above freezing air temperatures support streamflow for longer periods throughout the year. This coincides with a decrease in the snow season length as warm season lengths extend both earlier and later compared to the historical period, which has been identified in prior studies in the region.[83] Previous studies have also highlighted an increase in both winter-time precipitation and total year precipitation in the region over recent decades, along with an increase in extreme events. While peak flow events were projected to occur in the future, the number of these events is limited, making it difficult to ascertain with high confidence how many such events could be expected. However, this result does highlight a shift from the historical period, indicating a pattern of increased variability based on the distribution of streamflow events. While both GCMs generally aligned with the ERA simulations during the historical period after bias correction, each simulation presented different responses when it comes to mean streamflow, peak events, and total streamflow volumes in future decades. These differences in responses highlight a challenges when it comes to informed planning under climate change scenarios, particularly for decision-makers hoping to plan for extreme weather events in their region.

2.6.1 Model Limitations

While this effort helps to advance the understanding of Interior Alaska river systems under potential climate futures, it is also limited in certain applications, based on available resources, datasets, and observational data inputs, combined with the challenges of simulating an actively managed flood control project. Many of these issues are common in natural system modeling, which lead to uncertainty within modeling efforts.[85] These challenges can play an important role when exploring extreme events such as flooding, which can be particularly sensitive to non-linear responses, and may require alternative approaches, such as spatial frequency analysis derived events.[86] As GCMs are designed and tuned to consider global scale simulation of future climate change impacts, they are not intended to accurately represent local processes. Steps taken to guide local processes through GCM outputs may introduce added challenges for analysis. Stochasticity, model setup, and data complexity are all therefore important considerations with respect to limitations of this work to consider when exploring future changes in extreme events.

2.6.1.1 Stochasticity

One of the major challenges of using reanalysis data and downscaled GCM output is in the limited number of physics realizations available for many products in guiding those simulations and the computational complexity required to downscale them. Streamflow rates depend on numerous variables but are particularly responsive to short term precipitation rates. Due to the highly variable nature of extreme hydrological events, limited realizations restrict the ability to explore parameter sensitivity more effectively under uncertain futures, with storm systems playing a particularly strong role in flood behavior in this region, such as that of the 1967 floods. However, storm systems are challenging to represent within GCMs when it comes to frequency and extent and may be highly sensitive to model mechanics and parameterizations within the GCM.[87]

While the two GCMs used in this study indicate divergence in behavior, both for mean annual flow and extremes, simulations were limited to a single RCP, each with a single physics realization. Therefore, it is difficult to ascertain the level of internal model sensitivity when compared to the differences between models themselves or between RCPs. At the time of this study, the highly limited range of GCMs considered was driven heavily by computational resource availability, thus physical process-based downscaling across many scenarios or realizations was not possible. More recent advances in machine learning based approaches toward climate forcing may offer opportunities to improve the variability of outputs of a smaller number of physical process-based outputs in the future, offering a balance between computational efficiency and robustness of events.[88] On the other hand, the selection of the highest RCP in this work allowed for exploration of potential worst-case scenarios. Inclusion of a broader range of GCMs, combined with multiple physical realizations and RCPs, would allow for greater understanding of the range of plausible future climate change responses and may produce a greater degree of confidence in the variability represented within the hydrological simulations of these systems over time.

2.6.1.2 WRF-Hydro Model Setup

While necessary for the efficient completion of the project, choices in WRF-Hydro model design may have limited certain aspects of this modeling effort. Due to computational restrictions and data availability, forcing data was only available for three distinct time periods (2008-2017, 2038-2047, and 2068-2077). A lack of continuous data can present challenges in an environment that is also undergoing gradual long changes that may impact the degree of infiltration and runoff in the region, as permafrost thaw continues to alter subsurface hydrological behavior. Because each period utilized the calibrated model parameters, each time series began with similar starting conditions, until forcing data altered those landscapes. Under natural conditions, gradual warming would occur between decades, reducing permafrost and frozen ground thickness in the region.

That reduction in permafrost thickness would likely lead to an increase in groundwater storage, infiltration of surface water, and a potential decrease in peak runoff.[4] As a result, the 20-year gap between simulation time periods would likely produce differences in groundwater behavior that may not be present in the initial conditions for each of the simulations performed. Future work could consider the inclusion of either decadal spin-ups or a continuous series.

2.6.1.3 Bias Variability & Uncertainty

While the outputs of the WRF-Hydro model simulations indicated extended season lengths, increasing variability, and potential shifts in high-flow occurrence and seasonality, shortcomings in forcing data due to wet-bias, downscaling, and bias correction methods lead to greater uncertainty surrounding peak flows and are expected to continue to do so under the CMIP phase 6 models.[89] In the case of this study, monthly bias correction of climate projections (temperature and precipitation), and the limited overlap period in data sets (2008-2017), result in discontinuities within monthly temperatures. While preserving annual trends, this approach resulted in jumps between months, potentially influencing rapid springtime melt events as temperature thresholds are crossed. Modified approaches for this have been shown to improve hydrological outcomes surrounding seasonal boundaries.[90,91] It is therefore possible that this resulted in an over-emphasis on spring melt events in particular, as they are highly dependent on the rate of spring warming and peaks may be less extreme with more gradual temperature shifts between spring months.

The implementation of the WRF-Hydro model in Interior Alaska allows for future simulations to be developed to improve extreme events analysis in the region for riverine flooding. Improvements in the inclusion of permafrost dynamics, adoption of the ERA-5 dataset for modeling, extensions of the input forcing data to longer periods to allow for improved bias correction, and modification of the bias correction process to include annual cycles as opposed to monthly, would all be potential ways to improve future simulation and predictive accuracy. However, despite these shortcomings, the current WRF-Hydro model outputs offer insights into changes in seasonality (both length and timing of occurrences), changes in total streamflow and summertime extremes, and perspectives into the divergence of major model outputs based on temperature/precipitation interactions.

2.6.2 Implications for Decision-Making

Watershed and flood management programs are often based on historical conditions or flood recurrence intervals. This makes adapting to rapid change or unforeseen changes challenging, due to the long timelines required for policy changes, impact studies, acquiring funding, and development of solutions. The disconnect between planning windows and environmental responses from climate change, therefore, require an increase in forward-looking assessments of risks and attempts to understand potential shifts in extremes decades in advance. Within the study area, local governments have identified concerns surrounding increased potential for flooding events as part of emergency management and planning efforts, with a focus on flooding, groundwater seepage, erosion and scouring events, and increasing development in the region.[37] However, the ability to plan for future risks facing people and built infrastructure depends on the ability to understand how those risks compare to historical events.

Globally, floods account for a significant portion of disasters, with estimates indicating between 41 to 47 percent of disasters are caused by flood-related hazards.[92,93] As a result, the understanding of flood potential is a critical component to reducing risks in currently affected or future affected communities. When it comes to proactive approaches toward flooding, recent analysis indicates that the return on investment is high, with benefit-cost ratios for riverine flooding between \$5-\$8 saved in damages for every \$1 spent, with approaches ranging from mitigating infrastructure to improved building code requirements.[94] However, high levels of uncertainty,[95] or a lack of clarity as to sources of uncertainty,[85] may lead to difficulty in determining what level of proactive mitigation is justified. Simultaneously, decision-makers and planners are increasingly looking to models to identify potential local or regional scale challenges. Planning efforts must weigh a complex set of variables including model accuracy and uncertainty, as well as socio-cultural and economic factors, to include, for example, the economic resources available, tolerance for risk in particular communities or regions, and public support. Therefore, it becomes necessary to frame outcomes in the context of the level of confidence required to undertake planning, within the scales associated with hazards.

While efforts such as this study help to provide insights for decision-makers on potential future climate change impacts, it is important to be cautious in the interpretation of those results when developing major infrastructure plans. The results of this study show agreement between the two GCMs on increasing total streamflow and season length through the study basins, but they differ in their outcomes when it comes to extreme streamflow events. This creates challenges in terms of the development of solutions, such as rezoning, or the installation of large infrastructure, that may come with substantial costs or lead to displacement of populations over time or restrictions on local land use.

Instead, general trends may inform primary concerns but must be framed within the capacity of planners to contextualize the associated uncertainty. A preference for no-regret or robust multi-hazard resilient solutions, therefore, is important in multi-decadal planning.[81] Both of these GCMs indicate extended seasonality of streamflow, however, the GCMs also produce potentially very different futures, where streamflow extremes differ by time of year, intensity, frequency, and duration. This poses difficulties, when the development of large infrastructure depends on long lead times, significant resources, and has the potential to generate significant ecosystem impacts. Understanding the potential for these extremes, however, provides planners with insights as to how the infrastructure designs of the past may be limited under highly uncertain futures, and necessitates a potentially unforeseen need for flexibility in design.

The intent, then, is that while GCMs may not be able to highlight the future as if deterministic, the potential variability or uncertainty is communicated to the best of ability. This aligns with growing requirements to identify risk, scenarios, and uncertainty in applied modeling efforts.[96] From this, the outcome of this study is that, given the impacts under the two GCMs and RCP 8.5, along with the bias correction and presence of history exceeding events, that the relative change within each GCM over time represents the potential for extreme events that exceed those that have been dealt with since the developing of flood control infrastructure within the region. While the magnitude, frequency, and duration of those events is likely to vary, it provides room to understand the potential for those events well in advance of their occurrence, helping to provide planners with insights as to how the issues of awareness and preparedness can be addressed well in advance of expected extremes being realized.

2.6.3 Future Improvements

This study was limited by factors of both model and data dimensions, as well as those in the decision-making realm. Further studies may benefit from the inclusion of a broader range of RCPs and GCMs, as the limited range of scenarios may make it challenging to ascertain the full range of conditions that can be expected under future planning. A growing set of tools in the realm of machine learning may help transform these issues for extreme events[88] but may also face challenges in systems experiencing permanent state changes. While RCP 8.5 is the strongest warming scenario within CMIP5, it may not fully represent the range for flooding potential, under a moderate warming high precipitation future. Additionally, assimilation of dynamic permafrost data may improve insights for seasonal flooding or extreme event potential. Beyond this, there is a need for greater stochasticity of results to highlight where variability in short term outputs may influence extremes. This may also be an opportunity for further exploration of bias correction methods that could provide improved assessment of conditions within a fixed number of simulation inputs.

Another addition to this approach would be greater inclusion of affected planners. The inclusion of regional decision-makers in the evaluation of the results would allow for improved outreach and communication efforts, to ensure similar efforts reach those assessing planning efforts. Increasing the linkages between modeling efforts and planners is an integral component of actionable change going forward, due to the long timelines involved in infrastructure and planning-based mitigation and adaptation efforts. Improved linkage may also help to identify shortcomings in operational planning that may result from incompatibilities with modeling efforts.

2.7 Conclusion

In order to better plan for the dynamic needs expected under future climate change scenarios, it is increasingly necessary to model the potential for extreme events under different climate regimes and contextualize those outputs within decision-making efforts. This study explored the potential for future hydrological system changes in three Interior Alaska rivers, assessing dynamically downscaled outputs from two GCMs under RCP 8.5. Results indicate that under the highest warming pathways, feedback responses may vary substantially between models when it comes to extreme events, based primarily on model-dependent temperature and precipitation changes. However, both GCMs agree on long-term increases in mean and total streamflow, as well as the potential for extended streamflow season lengths in future decades. The results also indicate that as decades progress, streamflow may exceed those events which have been observed historically within these basins.

Additionally, this study highlights connections between increased seasonality and extended streamflow, and the potential implications for shifts in flood control efforts. The complexity of non-stationary processes present in the study region require greater integration between geophysical implications and disaster planning, to form a comprehensive understanding of potential hazards. This research sets a foundation for future work, recognizing a need for improved data assimilation, selection and correction of future projections, and greater inclusion of permafrost dynamics. Through these approaches, future efforts offer an opportunity to develop more robust and proactive adaptation strategies in systems like Interior Alaska, where significant change is already underway.

2.8 Acknowledgments

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Chapter 3: Arctic Sea Ice Decline and Geoengineering Solutions: Cascading Security and Ethical Considerations

3.1 Abstract

Climate change is generating sufficient risk for nation-states and citizens throughout the Arctic to warrant potentially radical geoengineering solutions. Currently, geoengineering solutions such as surface albedo modification or aerosol deployment are in the early stages of testing and development. Due to the scale of deployments necessary to enact change, and their preliminary nature, these methods are likely to result in unforeseen consequences. These consequences may range in severity from local ecosystem impacts to large scale changes in available solar energy. The Arctic is an area that is experiencing rapid change, increased development, and exploratory interest, and proposed solutions have the potential to produce new risks to both natural and human systems. This article examines potential security and ethical considerations of geoengineering solutions in the Arctic from the perspectives of securitization, consequentialism, and risk governance approaches, and argues that proactive and preemptive frameworks at the international level, and especially the application of risk governance approaches, will be needed to prevent or limit negative consequences resulting from geoengineering efforts. Utilizing the unique structures already present in Arctic governance provides novel options for addressing these concerns from both the perspective of inclusive governance and through advancing the understanding of uncertainty analysis and precautionary principles.

Keywords: geoengineering; securitization; ethics; climate change; arctic security; risk governance

3.2 Introduction

Geoengineering solutions are receiving increased interest in the Arctic as potentially important components of climate change interventions [**1**]; however, few studies have explored the implications from geopolitical perspectives, or the risks for regional security implications within the Arctic. Through a critical examination of the literature and a survey of emerging technologies and security concerns, this article will help to identify some important aspects of national and international security and ethical concerns within the region. Although it is likely that an international agreement will provide the “what” and “how” toward an organized approach, some nations will be inclined to avoid signing and ratifying such conventions or protocols, or they may even withdraw later after ratifying such agreements [**2**]. In the Arctic, special difficulties can be expected concerning international efforts. Even the variety of established definitions of the Arctic, including ecological, political, and geographic, illustrate some of the preliminary challenges. Although international frameworks tend to provide definitions based on consensus, existing or emerging definitions of the Arctic may not always agree, and any overlapping aspects into sovereign boundaries would expectedly cause concern. In particular, the effects of Arctic geoengineering would clearly have impacts in other regions and latitudes [**3**], possibly pitting the national interests of the northern nations against those of mid-latitude and lower-latitude nations, especially as national interests often involve the concerns and priorities of numerous domestic key and primary stakeholders [**4**].

The scope and purpose of this article is to examine the common circumstances involving the pursuit of Arctic geoengineering solutions through internationally based management within the context of security and ethics, as well as to emphasize the importance of proactive and inclusive governance approaches toward the development of solutions. The international relations process known as securitization theory, also known as the Copenhagen School (a framework to understand how issues may transition from non-politicized, to politicized, to securitized [**5**]), provides a way to explore potential areas where geoengineering may be viewed as an existential threat in the future (whether actual or perceived), in order to assess ways that potential conflicts could be avoided proactively through governance mechanisms. The philosophical understanding of consequentialism (a perspective that outcomes determine ethical impacts) under the premise of inclusive governance helps to provide effective guidance from which to analyze possible trajectories and recommendations. The first section will act as the baseline of the current understanding of Arctic environmental targets, to include the hydrosphere, atmosphere, and cryosphere. The following section will detail relevant geoengineering scenarios and technologies. Next, a breadth and depth exploration of security-related concerns, ethical considerations, and challenges that have the potential to lead to conflict will be presented regarding international collaboration. Finally, the last section offers potential recommendations on how to navigate these combined challenges through proactive risk governance-based approaches.

3.3 Current Environment of the Arctic

Arctic sea ice is a bellwether indicator for high latitude climate change, and it plays an important role in regulating the climate by acting as a barrier between the cold polar atmosphere and the warm ocean. Sea ice in the Arctic has retreated from long-term median values (Figure 3.1) over the past several decades and it reached a record minimum area of 3.41 million km2 on 16 September 2012 (Figure 3.1). This represents a 49% reduction, relative to the 1979–2000 climatology, and it caught the attention of scientists as well as the public. Sea ice decline has accelerated through polar amplification, as high albedo sea ice has been replaced by ocean, which absorbs sunlight and warms over the summer leading to further sea ice decline. Since 2012, each September, the minimum area continues to decline, as younger and thinner ice, which is easier to melt, has replaced older, thicker ice. Based on the latest projections of future sea ice from CMIP-6 simulations that were run with scenarios of expected anthropogenic forcing, summer sea ice is expected to disappear by 2050 [**6**]. The decline in sea ice has consequences for the Arctic as well as globally. Sea ice provides an important habitat for marine mammals, such as walruses and seals, as well as polar bears [**7**]. The disappearance of sea ice will change the way the ecosystem functions, and animals will either adapt or perish [**8**]. Indigenous peoples of the Arctic have strong cultural ties to the sea ice. They rely on sea ice for subsistence hunting and are impacted by the reduced safety from weaker sea ice, as more open water and thinner ice poses added risks [**9**]. The decline of sea ice is thought to increase the likelihood of a wavier jet-stream and severe cold weather events in the midlatitudes according to a growing body of scientists [**10**]. Sea ice is iconic, but the combined impacts of global warming are accumulating very quickly in many parts of the Arctic system. Studies show that as the permafrost thaws, it leads to increased greenhouse gases being released into the atmosphere [**11**]. The positive permafrost carbon feedback is of great concern for global climate stability. Some recent effects of warming are dramatic: methane blasts have been creating large craters in the Yamal Peninsula of Russia since 2014, and the most recent crater is 165 feet across [**12**]. Temperatures in the region continue to climb, and the Siberian town of Verkhoyansk hit a record high temperature of 100.4 °F in June 2020 [**13**]. The possible extinction of the iconic polar bear, and the potential of amplification of global warming from Arctic feedback to the climate system, is motivating diverse groups to find “expedient” geoengineering-based solutions (e.g., sea ice albedo control [**14**] and solar input management [**15**]) to the climate crisis.

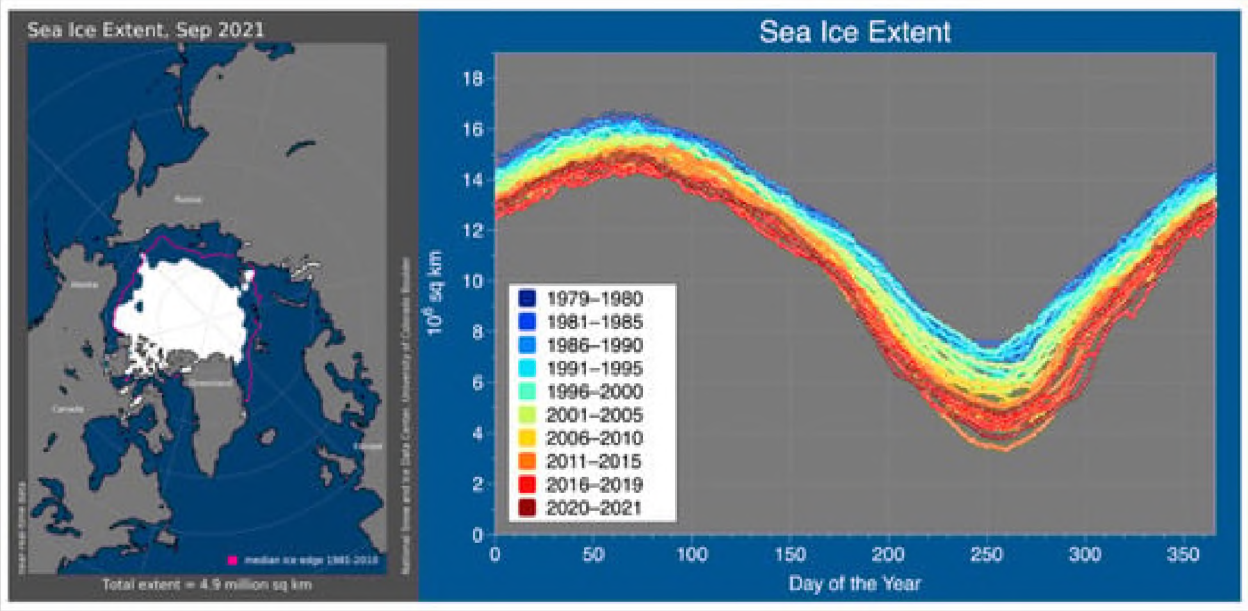


Figure 3.1: Arctic Sea Ice Extent

Left panel: sea ice extent (greater than 15% concentration) for the September mean compared with 2020 with record low 2012. Right: seasonal cycle of the daily Arctic sea ice extent in millions of square kilometers. Recent decades display sea ice decline in all months of the year. The left panel, and data for the right panel, is courtesy of the National Snow and Ice Data Center, University of Colorado, Boulder. The right panel graphic is modified from a DataGraph template.

The decrease in sea ice is expected to lead to increased traffic from various activities [**16**]: resource exploration, new shipping routes, expanded scientific activities, tourism, geoengineering, and expanded fisheries. However, a lack of physical as well as policy infrastructure needs to be addressed in order to ensure environmental security in the Arctic. In this article, we focus on geoengineering activities as a potentially disruptive technology that could destabilize the polar north region [**17**]. Any proposed solutions should therefore include an understanding of climate change, geopolitics, and ethical considerations.

3.4 Arctic Geoengineering Solutions

Numerous options have been proposed for the deployment of geoengineering in and around the Arctic to protect existing sea ice or to promote further ice buildup. The majority of identified solutions are focused on reducing solar radiation from reaching the ice surface [**18**], delaying the melting of ice [**19**], increasing the production of winter ice [**20**], or a combination of these mechanisms. These efforts may be based locally in the Arctic, or remotely, and they vary substantially in cost and complexity. Some of the most involved methods require complex infrastructure systems and significant economic investments in order to achieve their results. Additionally, the degree to which these approaches are reversible or irreversible influences the potential risk associated with any proposed solution. This article is not focused on the validity of specific methods of sea ice-based geoengineering, but rather, on the increasing likelihood that in the near future, it is plausible that nation states, or powerful independent actors, may unilaterally deploy these efforts widely. Moreover, they may do so before other nation states or international actors can intervene or counter their methods. It is these factors that elevate the importance of this issue, and the need for preemptive and proactive measures and awareness surrounding geoengineering in the Arctic, to both prevent unnecessary escalation between Arctic powers and minimize the risks to Arctic residents. Although it is not the primary focus of this article, we will briefly explore a range of these options in order to contextualize calls for proactive solutions and agreements.

3.4.1 Solar Radiation Based Geoengineering

Reducing solar radiation from reaching the Arctic, and specifically sea ice, can be achieved through either blocking or reflecting sunlight and can theoretically be deployed anywhere between the surface of the ice, all the way to distant points between Earth and the Sun. Some of the more drastic proposed options in the past have included the deployment of a sunshade in space, located at the L1 Lagrange point, which would block a portion of solar radiation from reaching Earth [**21**]. This would be an incredibly costly option, with the potential to reduce solar radiation on a global scale, and it would require an estimated cost in the order of trillions of dollars to achieve; however, such an effort has the potential to generate a large scale international conflict over which nations, actors, or powers control that system, and to what extent it poses a greater net risk than it may help to offset. Closer to Earth, the injection of aerosols into the stratosphere to reflect or diffuse incoming solar radiation has been not only proposed, but there are groups actively working toward limited testing to better ascertain the benefits and risks [**22**]. Although these tests can be performed regionally, it may be more difficult to contain locally due to the atmospheric dispersion of those aerosols. Regionally, and closer to the surface of the ice, a number of projects have been proposed to limit surface albedo, ranging from tiny silica-glass beads [**14**] coating the surface of the ice, to the deployment of reflective sheets or blanket type materials to cover existing ice. The latter option has been explored in glacial regions to reduce melting with some success, although at substantial cost, and it is expected to have a limited broader application [**23**]. All of these efforts, although they vary in scale and proximity to the Arctic, offer ways to reduce the melting of Arctic sea ice through the reduction of incoming solar radiation.

The difficulty or ease of deployment of geoengineering efforts also varies greatly, as does the reversibility of different methods. Although a sunshade may not be easily managed without significant investment and awareness, and would likely require substantial international collaboration and support to achieve, deploying large amounts of microbeads in the Arctic would be far more achievable in the near future, at a significantly reduced cost. Options which require little to no international collaboration, and can be rapidly deployed, become a feasible route for nation states or independent actors independently of the global consensus, and therefore, they are a larger point of concern regarding the unintended consequences of those actions and the repercussions for international relations.

3.4.2 Thermal Geoengineering for Ice Preservation or Production

Aside from reducing solar radiation, other solutions have been proposed to either reduce the ocean melt of sea ice or increase the production of winter sea ice. One of those proposed solutions depends on reducing the melt-off of existing near-ocean glacial ice by developing artificial sills to prop up and isolate the glaciers or ice sheets in areas such as Greenland, where seasonal waters may contribute to substantial warming and thawing events. The intention is that this separation would help to maintain these ice sheets in summer seasons and prevent catastrophic collapse [**24**]. Other solutions point to the deployment of large-scale wind-pump systems to help cool sea ice in summer and to bring water to the surface in winter to promote greater ice production during the cold season [**25**]. Both options are extremely costly and would require large investments both in economic and political terms, likely placing them in the realm of nation states. This is not to say lower cost solutions may not be developed for thermal geoengineering approaches, but few have been proposed at this time; however, solutions in this area may not be effective in the long-term in the face of continued warming, as warming at the global level is likely to outpace many of the reductions these solutions hope to address. Additionally, the unintended consequences of shifting Arctic currents and atmospheric conditions as a result of these methods are not yet well understood and could lead to potentially damaging results for the region, from fundamental changes in ocean dynamics to impacts on marine and Arctic species.

Both solar radiation management and thermal management technologies provide mechanisms for the preservation of existing ice, or the potential for the growth of new ice. In each category, options range in scale from extremely localized to global level mega infrastructure projects, with varying degrees of reversibility and cost to implement. These factors further strengthen a need for understanding these processes prior to implementation, to ensure that a holistic picture of any impact is well understood and is communicated as part of any deployment efforts.

3.5 Security-Related Challenges with International Collaboration

Additional concerns surrounding climate change geoengineering solutions involve security interests. Of the many frameworks from which to examine security issues, Buzan provides a fundamental international relations theory widely regarded as the "securitization" theory [**26**]. This architecture provides an effective framework to analyze security dynamics and security issues through a variety of actor levels (individual, sub-state, state, and international systems) and a wide range of sectors (political, economic, military, social, and environmental). Floyd extends this in her examination of environmental applications of the framework and asserts the need to consider consequentialism studies in order to properly evaluate the morality of (possible) (de)securitization outcomes [**27**]. The securitization theory bypasses the debate concerning the extent to which threats are either real or perceived. Instead, it offers a way to examine security in the ways that issues are socially constructed as a threat. The social construction of a threat is conducted in what is known as a speech act, where a high-level figure or collective articulates an issue in a way that is meant to elevate an issue that is managed in the political sphere to an escalated securitized level. This is an important component in the potential securitization of geoengineering efforts, as the threat need does not be objectively real in order to generate extreme measures in response.

However, the speech act alone is not enough. According to Van Munster, a securitizing speech act needs to follow a specific rhetorical structure, which is derived from war and its historical connotations to survival, urgency, threat, and defense [**28**]. This leads the Copenhagen School to define securitization as a speech act that must fulfill three rhetorical criteria. It is a discursive process by means of which an actor (1) claims that a referent object is existentially threatened, (2) demands the right to take extraordinary countermeasures to deal with that the threat, and (3) convinces an audience that rule-breaking behavior to counter the threat is justified; therefore, it is possible that even in the absence of environmental harm, geoengineering could be constructed as a threat in a variety of ways.

From a normative approach, consequentialism provides an effective means from which to examine issues involving the moral rightness of an act or something related to an act, including motives and policies. Classic consequentialism developed through a variety of claims, often involving prominent categories of theories, including (1) objective consequentialism, which involve theories that focus on actual or objectively probable consequences, and (2) subjective consequentialism, which involve theories that focus on intended or foreseen consequences, whereas non-traditional, proximate consequentialism, describes how the moral rightness of an act is determined only by proximate consequences [**29**]. Taken together, securitization and consequentialism provide powerful conceptual guides that are useful for examining Arctic geoengineering challenges toward collaborative agreements and efforts.

With little doubt, diplomacy and science will likely be charged to provide leadership in global geoengineering endeavors, including the Arctic region; however, to assume that an Arctic geoengineering solution will be developed and implemented through naturally peaceful and cooperative means might be a mistake. Additionally, domestic actors will likely pressure national authorities with concerns of local negative impacts. The securitization process helps to describe how such non-military concerns can result in issues of national security and interests, which could greatly affect the ability of an international coalition to adopt solutions; however, studying the securitization and consequentialism circumstances for the Arctic could help facilitate cooperative efforts toward resolving tensions in order to achieve desired regional objectives. At the very least, such considerations could help to manage overall expectations, as well as to acknowledge legitimate and competing perspectives.

Such challenges remain the purview of the diplomatic corps of the world who are well trained and experienced in dealing with multinational issues and tensions. For the circumpolar North, the Arctic Council represents the lead international institution with significant proficiency in overseeing efforts in support of environmental and Indigenous solutions. Although unlikely to directly oversee geoengineering efforts for the Arctic, the organization provides a highly relevant example of what coalition-led efforts offer in the realm of scientific uncertainty and understanding that is deeply connected to regional stakeholders. It is plausible that the Arctic Council could contribute to any number of components, whether through efforts to improve scientific understanding, through enhanced monitoring, or through the establishment of guidance based working groups, making the lessons learned there additionally valuable to any implementation strategies. Many Arctic Council projects and initiatives involve the study of processes that affect the entire region, not unlike geoengineering. The Arctic Council is by design a consensus-based organization, where the eight member nations retain decision-making authority, and six permanent participant groups representing Arctic Indigenous peoples have full consultation rights. Of note, the Arctic Council does not engage in issues of military security [**30**]. As a result, topics involving sensitive national security interests cannot get in on the agenda, or they are otherwise rejected if member nations are instructed or compelled to do so. The securitization process warns us that issues can go from acceptable dialogue and consideration to a diplomatically difficult situation—possibly even elevated to an emergency level in extreme scenarios. To maintain a geoengineering dialogue in a collaborative or consensus building environment such as the Arctic Council, it will require an understanding of potential conflict and competition points in advance to prevent or limit the securitization of these issues.

Within that context, it is not only possible but plausible that nations may not easily agree to geoengineering solutions as a result of conflicting national security interests. To disregard such opposition, even in an adversarial-based system (such as the United Nations), might lead to the development of dangerous consequences. Unlike the Arctic Council, it would be anticipated that the responsible body with regard to Arctic geoengineering would likely have two overarching organizational objectives: (1) identifying and defining the problem(s) to be resolved in a typical framework instrument (e.g., Vienna Convention), followed by (2) establishing the implementation, maintenance, and inspection/review requirements in a typical protocol instrument, such as the Montreal Protocol [**31**]. What determines the structure and authorities of any potential geoengineering-related organization is yet to be seen, although the history and process of similarly related endeavors are well-known and documented. Part of any international organization's efforts involving management of geoengineering will invariably include a significant amount of interdisciplinary literature reviews. For example, not only will the impact of global climate systems as a result of geoengineering need to be relatively well known, but a critical understanding of the processes and norms of securitization and consequentialism will also need to be a part of considerations where tensions over issues are concerned. It is of paramount importance that international organizations are set up for success from the start, because the alternatives are often exponentially counter-productive, and delays late in the process may lead to a failure to reach diplomatic solutions.

As with any international treaty/convention, the most commonly recognized types concern international law [**32**], but not all nations become full-party members, nor do all nations remain members. This would likely be the case with any framework convention and protocol involving Arctic geoengineering, especially because the vast majority of environmental agreements tend to function on the premise of reducing production, consumption, or processes, rather than the introduction of engineering-based solutions. For example, the international solution for dealing with the ozone problem as per the Montreal Protocol involved a significant reduction in use of the substances responsible for the problem. Other agreements have found solutions in reductions or a change in human behaviors, such as the precautionary moratorium on unregulated high-seas Arctic fishing activities, until a greater understanding of impacts could be achieved [**3**]; however, geoengineering solutions in the context of this article will likely involve adding something new to the environment, which, once released, might not be as easily controlled. This circumstance would be fairly novel and especially difficult as part of an agreement, based on ongoing monitoring and management requirements. Unlike other conventions where non-party member nations might not interfere with the agreement, geoengineering in the Arctic atmosphere would undoubtedly draw active opposition from non-party members. Whether in the Arctic, Northern Hemisphere, or anywhere else, affected nations could have a justification for withholding support, knowing full well that what happens in the Arctic does not stay in the Arctic.

This leads to the potential for a range of scenarios, where independent or unilateral attempts at geoengineering solutions may have consequences outside the intended area of impact, and may affect the food security, energy security, and other forms of security within other nation's political boundaries. Modeling efforts have already identified that asymmetrical approaches to geoengineering in the Arctic may lead to alterations in the Inter-tropical Convergence Zone (ITCZ), creating a reduction in local precipitation in portions of the Southern hemisphere [**33**]. Although the oceans and atmosphere form components of the global commons [**34**], alterations to those features have the potential to directly affect areas within terrestrial boundaries. Prior conflicts over fishing resources, including access and distribution, offer examples here as to the connections between shared resources and the potential for conflict. Previous efforts at geoengineering, such as iron fertilization, when connected with issues of fishery management, may provide insights as to the ability for such issues to become securitized [**35**]. Additionally, when framed as a disruptive technology, nation-states may be incentivized to develop cutting edge systems that produce improvements to regional outputs, whether from fisheries, agriculture, or other means, at the cost of neighboring or even distant regions, creating regional losses that may generate antagonistic perceptions.

3.6 Ethical Concerns with Broader Impacts

Although ethical considerations often depend on local or regional norms, the differences between these norms and how they are prioritized can lead to larger concerns or conflicts between regional actors or nation states, and domestic issues are not always limited by national boundaries in the Arctic. Although many attempts at geoengineering or climate engineering may originate outside of the Arctic, the impacts are likely to be observed earlier within the Arctic, where climate response is often amplified [**36**]. When it comes to geoengineering, the risks go beyond merely technical or security considerations, and may have far reaching ethical implications. Those ethical impacts have the potential to drive international conflict; therefore, it is important that ethical considerations play a role in the plans to enact geoengineering efforts. These considerations involve questions such as: What is the target climate, and who determines it? What is the likely distribution of impacts among Arctic nations? Who, or which groups, are responsible for the development and deployment of proposed solutions? To what extent can we seek to understand the unintended consequences? What is the potential for abuse of these systems? These questions primarily relate to two areas of ethical concern: (1) consequentialism, or the idea that end results determine whether or not the efforts undertaken were justified, and (2) inclusive governance, an approach examining the inclusion of those affected by decisions, in both processes in which efforts are undertaken and the distribution of outcomes [**37**].

3.6.1 Target Climate

One of the early issues with the implementation of geoengineering efforts is based on the question of target climate conditions within a region, and who determines which levels are acceptable. The now well-known recommendation to limit changes to 2 °C above pre-industrial temperatures was proposed as far back as 1990 through a report from the Stockholm Environment Institute [**38**]. At the time, this was initially seen as a less preferable option to a 1 °C target, but one that might be more achievable, along with efforts to limit decadal rises to no more than 0.1 °C in order to reduce negative impacts. The IPCC has since mirrored these assessments, but has provided analysis for risk levels in the 4 °C range as well, although this latter target is expected to have far more negative impacts globally [**39**]. More recently, concerns have mounted for the potential damage of a 1.5 °C level increase above pre-industrial conditions, as evidence of change has accelerated [**40**].

Although a few areas are likely to aim for pre-industrial conditions, the target climate for geoengineering efforts is likely to vary for differently affected countries. Regions that have already made significant efforts to adapt to recent or current states of climate may even find a return to previous climates to be detrimental to their current practices, if not dangerous, leading to the potential for counter-engineering efforts by those negatively affected. Others still may aim for a target climate that has not yet been experienced, due to perceived benefits it may offer through increased natural resource access, economic growth, agricultural potential, strategic advantages, or to minimize the need to reduce emissions to previous levels [**41**]; however, any reductions from the current climate are likely to face substantial challenges and may take decades to fully achieve success [**42**]. The attempts to meet these goals are also likely to result in a range of experimentation efforts in the meantime, with short term and localized effects expected to contain significant uncertainty. Although international agreements may result in long term targets, such as aligning with the Paris Agreement, nation-states may find differences in what they consider optimal conditions [**43**]. The disconnect between these goals for nation states has the potential to lead to conflict, where a nation focused on reducing the rising sea levels to coastal communities impacted by the loss of protective landfast ice may contrast with the goals of a nation interested in increased Arctic natural resource development through improved access to offshore energy reserves made more accessible as a result of sea-ice decline. In the case of unilateral actors, the consequences of actions may be borne by different nations than those that initiate climate intervention efforts, especially if not addressed through inclusive forums that represent the range of concerns.

3.6.2 Distribution of Impacts

Results of geoengineering efforts pose additional challenges for Arctic residents, where impacts are unlikely to be evenly distributed, whether geographically, demographically, or socioeconomically [**44**]. Larger temperature swings due to global emissions are already being experienced in northern regions, as polar amplification has led to more significant shifts in temperature increases toward the poles [**45**]. With winter temperatures projected to increase by as much as 13 °C in the region under high emissions, as opposed to global averages in the 2–4 °C range, it is clear that the impacts of climate change will not be uniform, and that the Arctic is likely to see radical shifts in climate [**46**]. Similarly, geoengineering efforts have the potential to cause uneven changes when attempting to reduce warming, and may lead to larger swings in climate conditions, challenging localized adaptation efforts, and native plant and animal species already threatened under climate change [**47,48**]. Even the methods of implementation will likely alter the spatial distribution of climate adjustments, with aerosols having widespread effects, and local surface albedo related controls are more likely to be largely contained to regional changes, but may also have substantial effects. The extent of any geoengineering approaches in that case will depend on the range of communities and infrastructure within the area of impacts, and the ability of those groups to withstand those impacts.

As with the impacts of climate change itself, areas that are currently near change thresholds or tipping points are likely to be affected more rapidly, and more disproportionately through any geoengineering efforts. In the Arctic, this affects a wide range of communities, including but not limited to those in low lying coastal regions experiencing increased storm surges and erosion [**49**], those in areas where permafrost is reaching or surpassing thaw temperatures [**50**], and those in areas where shifts in the seasonality of the climate is undermining historical and traditional uses [**51**]. Additionally, many of those already impacted by climate change are facing resource constraints, making adaptation and mitigation efforts more challenging. As a result, having the ability to adjust to externally generated and potentially rapid shifts from geoengineering efforts poses additional challenges [**52**]. Efforts taken to adapt will proportionately be more costly, and the need to consider increasingly uncertain impacts from climate change becomes more difficult, including added risk assessment challenges [**53**]. This is not to say the existing challenges under climate change will not also pose many risks, but rather, that it needs to be considered as part of planning efforts that geoengineering may disproportionately and increasingly challenge vulnerable populations. Efforts undertaken without considering those factors may exacerbate them, especially for those communities lacking the resources for expensive mitigation efforts. Taken together, the disproportionate effects from geoengineering efforts in their distribution will require additional care to avoid the creation of unintended consequences. From a consequentialist perspective, the impacts to those at the local or regional level should not be overlooked in an effort to address challenges in other regions. Any nation or independent actor undertaking such intervention or geoengineering efforts must recognize that the possibility also exists to affect areas outside of their terrestrial boundaries, which may escalate cross-boundary tensions.

3.6.3 Unintended Consequences of Interventions

Although current efforts have primarily been focused on computer simulations, and in rare cases, small-scale experiments, once large-scale efforts are undertaken, there exists the potential for substantial unintended consequences, either due to unidentified interactions, potential miscalculations, or lagging responses. Although a sense of urgency exists among many with regard to the need for solutions to climate change, without proper due diligence, proposed solutions have the potential to exacerbate current challenges and add tension between nation states and their citizens, who bear the result of any experimentation. Under the concept of consequentialism, although the aim for expediency may be well intended, failing to understand the complex interactions leads to the concern that poorly understood outcomes may lead to a net negative outcome, worsening the situation for those affected. Although the available number of real-world experiments in geoengineering has been limited, the deployment of large renewable energy systems is more prevalent and can act as an example of positive intentions, resulting in potential net negative outcomes once studied. Solar and wind technologies, for example, are often recognized as a way to reduce carbon emissions and replace fossil fuel consumption through renewable pathways, and those technologies have received widespread support [**54**]; however, recent studies indicate that in large-scale deployments, depending on placement, the near surface changes to albedo and atmospheric conditions may produce net-warming [**55**], disruptions of local climate patterns [**56**], reduction of wind speeds [**57**], and a loss of precipitative transport inland [**58**]. By some indications, wind farms may "need to operate for more than a century before the warming effect over the Continental US caused by turbine-atmosphere interactions would be smaller than the reduced warming effect from lowering emissions" [**56**].

In addition to failing to mitigate carbon production, these studies highlight that mitigation efforts hold the potential to alter agriculture, water availability, the frequency, intensity, and duration of natural hazards, and a range of other issues that have the ability to amplify climate challenges and could increase the potential for conflict. Concerns over the understudied or poorly understood consequences of geoengineering have already led to push back from some Indigenous groups in the Arctic. In March of 2021, the Saami Council, representing the Saami (Sámi) people, wrote an open letter to the Stratospheric Controlled Perturbation Experiment (SCoPEx) Advisory Committee, which is part of a project by Harvard University attempting to test stratospheric aerosol injection technology in Sweden [**59**]. The letter voiced several issues, including the potential for termination shock, "irreversible sociopolitical effects", and concerns that the team did not "have any representation from the intended host country". Citing concerns from the Saami Council and environmental groups, Sweden's space agency cancelled the flights that would have been the first active test of aerosol injection technology [**60**]. These challenges further highlight the need for an inclusive risk governance approach, to ensure stakeholder concerns are a component in the design and deployment of eventual intervention methods. Additionally, such an approach would provide a mechanism to communicate risk more effectively between groups.

3.6.4 Competition and Representative Decision-Making

In general, the government has a compulsory or requested role in managing negative externalities, often by a higher level of government or an adopted international body. Atmospheric geoengineering comes with many concerns involving negative externalities, in particular, environmental externalities. Traditionally, environmental externalities "arise when certain actions of producers or consumers have unintended effects on producers and/or consumers" and they become negative when an "action by an individual or group produces harmful effects on others"[**61**]. The OECD further defines environmental externalities "As a consequence of negative externalities, private costs of production tend to be lower than its "social" cost, where it is the aim of the 'polluter/user-pays' principle to prompt households and enterprises to internalize externalities in their plans and budgets [**62**]". Geoengineering does not fit these definitions very neatly, but the premise can be easily understood and adopted; however, whereas international agreements can help to manage expectations with externalities, the magnitude of uncertainty concerning geoengineering impacts would likely test the limits to which principles and norms could help resolve future issues.

Developing a multinational effort to confront issues often requires an effective understanding of how to manage domestic and foreign interests in order to achieve a "yes" regarding agreements or acceptability of proposals [**63**]. Proposing and committing to obligations and non-obligations as part of an agreement will quickly prove how difficult such endeavors are when trying to compromise within a spectrum of different interests. In addition to the theory involving 'securitization' discussed previously, Oran Young provides a useful macro-level approach when considering governance issues through three main fragmentations, including (1) jurisdictional, (2) sectoral, and (3) institutional [**64**]. Increased fragmentations expectedly create a parallel-like increase in the need for governance, not unlike the justifications for government intervention.

Young explains that “jurisdictional fragmentation is a matter of the division of a region into a number of segments that are distinct with regard to their jurisdictional status while sectoral fragmentation, on the other hand, arises from the existence of distinct regimes dealing with specific activities, such as shipping, oil and gas development, fishing, and so forth”. Institutional interplay and fragmentation occur when “responsibility for managing distinct human activities is distributed across a variety of public-sector agencies” [**64**]. Fragmentation as an example of structured organization in thinking not only helps to develop a meaningful understanding of competitive and/or conflicting issues, but also how interests can be understood and managed both internally and externally in a proactive manner.

As seen with issues relating to unintended consequences from geoengineering-based climate interventions, groups within the Arctic have already voiced concerns about the lack of representation regarding impactful decisions affecting the region. In the case of the Saami objections, the lack of inclusion in the decision-making process was an important concern, as those in the area of testing perceived that they were required to bear a disproportionate risk, without the ability to properly assess or contribute to the test design process. Similarly, in Alaska, concerns have been voiced regarding the Arctic Ice Project (formerly Ice-911), an effort to distribute silica-glass beads to improve ice albedo, and the inclusion of local perspectives on the assessment of risk [**65**]. Local critics of the effort have argued that the project may pose additional risks for residents and wildlife, and that a lack of community input may be adding another layer of complications for those already attempting to adapt and understand ecosystem changes, without the means to address those changes proactively [**66**]. It is particularly important to note that different communities and regional governance authorities are not homogenous and will have different perspectives as to the acceptable level of risk associated with any potential impacts. These mismatches have the potential for both domestic and international conflicts to arise. Understanding those perspectives will be an important concern when it comes to issues of self-governance and acceptance of technologies.

Which groups are responsible for deployment efforts plays an important role in understanding the level of support or opposition that geoengineering solutions are likely to receive. Inclusive governance is well suited to these challenges, because it has the potential to proactively identify conflict points, identify areas for strategic coalitions, and help balance concerns at domestic and international levels [**67**]. Through the use of inclusive governance approaches, the range of concerns can be better identified in advance, reducing the likelihood of the failure of proposed agreements once they reach the international level. As an example, longstanding concerns have existed in the Arctic regarding the causality of climate change and the disproportionate impacts of outcomes in a region that has been affected by outcomes not entirely within its control. In the past, this debate has centered around energy production and resource use concerns, where oil and natural resource extraction have been both an economic boon [**68**], but also a source for environmental damage and cultural upheaval through global consumption and local degradation [**69**]. The emergence of geoengineering may amplify this debate, where effects may be far removed from where experiments or full-scale deployments are conducted. Although groups impacted by geoengineering are likely to vary substantially, it is important to consider who or which groups will be responsible for the approval, development, and deployment of any geoengineering solutions. As negative impacts are unlikely to be equally distributed, it is imperative that those negative impacts are understood to the greatest extent possible prior to engaging in broader efforts, especially for non-reversible efforts. This approach toward inclusive governance has gained traction throughout the Arctic, as the Arctic Council has worked to balance the needs of nation-states with those of Indigenous permanent participants, and newer frameworks are emerging to support those efforts [**70**]. It has the advantage of assessing and responding to local needs early on, leading to greater support once initiatives move forward at the international level.

The concerns listed in this section are not exhaustive, but rather, they note areas that begin to highlight the uncertainties and challenges facing the development of solutions in the polar north that reduce the potential for escalation and the likelihood of consequences that could be perceived as antagonistic regionally. Any of the factors discussed previously have the potential to produce conflict, both within nation states and between them. They also have the potential to disproportionately affect those living in, and those who are connected to, the region in ways that may not always be clear initially. As geoengineering makes its way into wider adoption, and as nation states begin exploring it as a stopgap for current warming trends, it will be critical to consider these factors, and to include those affected by the decisions in the process, both to minimize negative outcomes for residents of the region, but also to avoid unnecessary escalation toward conflict.

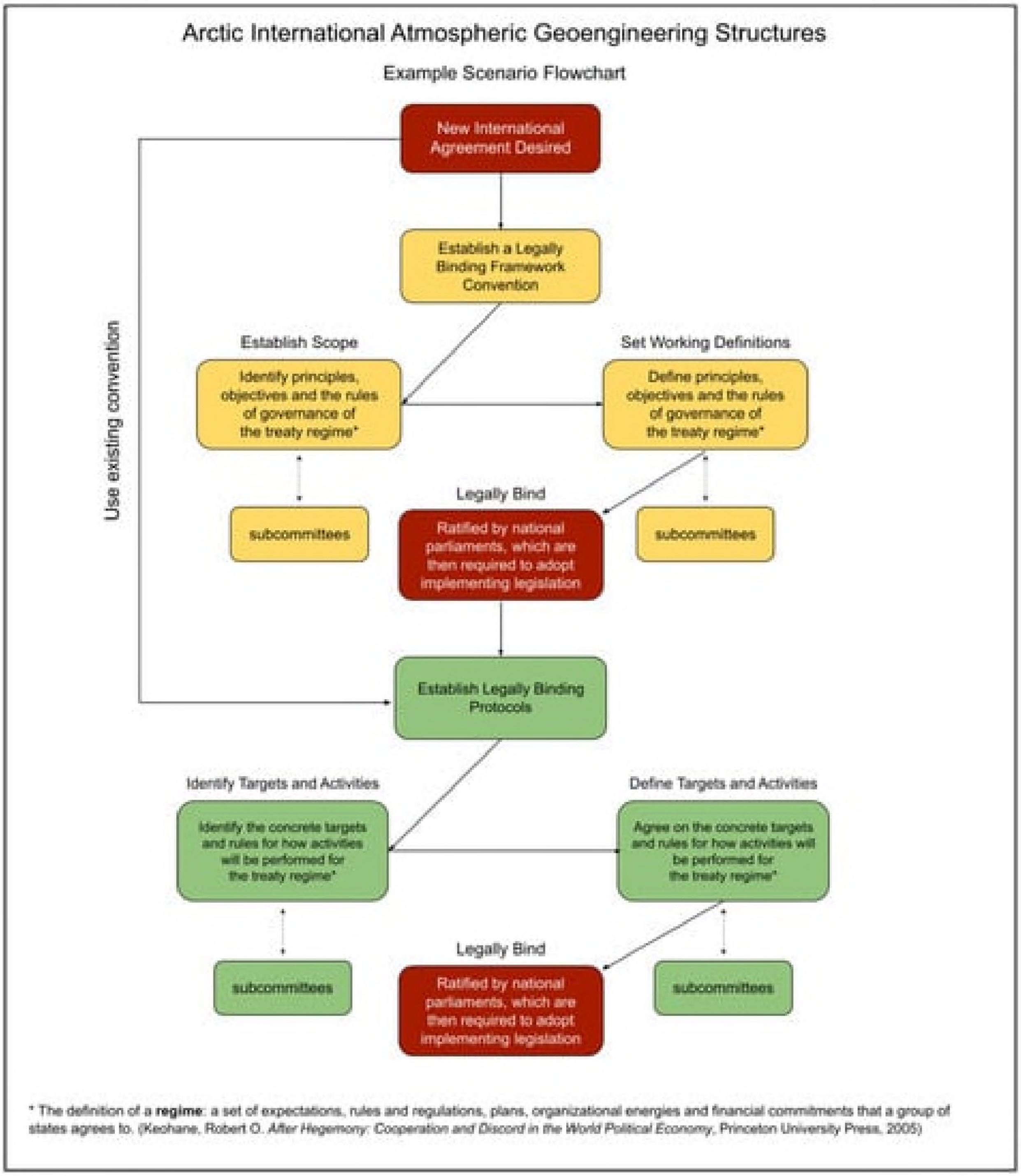
3.7 Navigating the Combined Challenges

The combination of declining sea ice and increased interest in the region, as well as the expansion of proposed solutions via geoengineering in the Arctic, makes the eventual deployment of those solutions much more likely. Without global agreements prohibiting the practice of geoengineering or providing regulatory oversight, nations will become increasingly motivated to take it upon themselves to protect their own interests to the greatest extent possible. This type of unilateral action not only poses problems from the perspective of international relations, but it also increases the chances of a lack of inclusive governance approaches leading to an increased risk of conflict at multiple scales of analysis. Although numerous approaches have been proposed for limiting the decline of Arctic sea ice, (e.g., solar blocking aerosols in the region, materials to reduce surface albedo on sea ice, or the use of complex thermal based systems to reduce losses or allow more ice to form), they vary substantially in cost, complexity, and reversibility [**20**]. Such solutions are continuing to push forward as a necessary means of preventing sea-ice collapse and further amplification of Arctic warming [**14**]. If the assumption is that geoengineering in the Arctic is not a matter of if, but when, then an important question becomes; to what extent will attempts to reduce sea ice loss through geoengineering by sovereign nations or independent actors result in an increase in geopolitical tensions? Secondarily, how can the international community identify and manage tensions generated by geoengineering approaches proactively [**71**]?

3.7.1 Additional Considerations

When it comes to the protection of Arctic sea ice, most of the affected domain currently resides in international waters. Any actions in those waters would be subject to a very limited range of international agreements, with minimal, and as of yet, untested enforcement capacity. Although the UN Convention for the Law of the Sea (UNCLOS) instituted agreements on ocean-based pollution, such actions taken in the attempt to preserve or protect environmental concerns could be seen as exclusionary to that purpose, and without the inclusion of the precautionary principle, they may be difficult to enforce [**72**]. Instead, vague applications may allow for sovereign nations or independent actors to carry out widespread geoengineering efforts in the Arctic with little recourse via current international law. As a result, the determination to engage in geoengineering in the Arctic has the potential to succumb to traditional power politics, as individual nations determine for themselves the best course of action for their own interests. Although this does not preclude the possibility of cooperative or collaborative efforts among nations, lacking an enforceable framework is also unlikely to prevent independent actions. The actions taken on individual or nation-state levels have the potential to produce negative consequences for other nations and groups when not enacted in a holistic and comprehensive manner. The scale of these consequences then acts as a point of division or securitization (such as the promotion of geoengineering as an existential threat requiring extreme response measures) for geopolitical actors, straining relations in an otherwise relatively stable political region of the world [**26**].

To minimize uncertainties and tensions involving collaborative processes regarding counter-warming issues, proactive agreements need to account for many factors, including geopolitical and national-interest concerns, especially as states begin to address the critical challenges of sea-ice loss and other climate related impacts. Although global geoengineering efforts may come to depend on large scale agreements under the United Nations, Arctic focused efforts may be achievable on shorter timeframes, with a specific focus on hemispheric changes, requiring Arctic leadership and oversight. Throughout the development of the agreement process, components of the final product can be streamlined by adopting and utilizing specified topical subcommittees including a subcommittee on the ethical deployment of geoengineering solutions in the Arctic (Figure 3.2). Even a non-binding forum would provide Arctic stakeholders with the opportunity to express concerns, highlight potential negative feedback from geoengineering solutions, and to facilitate studies of awareness and potential impacts of such approaches prior to their implementation. These subcommittees could help ensure due deliberation throughout the overall process as well as in the development of final product(s) and agreements. Such a subcommittee could potentially benefit from the work of the Arctic Council and their model of representation of affected groups. Additionally, the Arctic Council might be able to provide specific value-added aspects that could be used for regime updates and maintenance. As prior research efforts have indicated, many of the social consequences of these solutions are still not well understood, and will require greater efforts by technologists, social scientists, and policy makers to begin exploring the possible outcomes [**73**]. Although the Arctic is experiencing changes at a rate faster than most of the globe, this also provides an opportunity for the Arctic to take a leading role in developing responsible approaches to the implementation of radical solutions in the form of geoengineering. The development of international forums on the issue may help to guide these efforts toward maximum benefits while helping to reduce the potentially disastrous consequences for international relations and Arctic actors.



Arctic International Atmospheric Geoengineering Structures

Example Scenario Flowchart

* The definition of a **regime**: a set of expectations, rules and regulations, plans, organizational energies and financial commitments that a group of states agrees to. (Keohane, Robert O. *After Hegemony: Cooperation and Discord in the World Political Economy*, Princeton University Press, 2005)

Figure 3.2: Sample possible flowchart for international agreements.

3.7.2 Risk Governance

To explore the prior questions, it is important to look at the problems from an approach that considers not only risk, but the perception of potential risk, as both play an important role in international relations and the likelihood of conflict. The Risk Governance framework, originally outlined by the International Risk Governance Council in a 2005 white paper, which has since expanded, proposes a multi-phase process toward governance, to include (1) pre-assessment, (2) risk appraisal, (3) risk characterization and acceptability judgements, and (4) risk management [**74**]. A key difference from other governance frameworks is a focus not only on assessed risk but also on perceived risk, as decision-makers often rely on perceived risk when making decisions under uncertainty. This focus on perceived risk allows for potentially affected stakeholder or rightsholder concerns to be integrated into the planning process proactively, and it also identifies a range of areas that may lead to internal or external conflict through their consequences. An earlier focus on cultural concerns during the pre-assessment phase, as recommended, could help identify the types of issues that led to the conflict over proposed aerosol delivery feasibility testing in the Saami lands in Sweden. Additionally, added emphasis on stakeholder and researcher collaboration could help to better identify the unintended consequences at a regional level, based on local stakeholder concerns and priorities. This approach has the potential to not only better align stakeholder and decision makers on risk tolerance, but newer approaches also consider the substantial uncertainty associated with emerging technologies.

In 2015, guidelines were released for emerging risk governance, which provided additional recommendations for risks that hold high uncertainty, such as geoengineering, and they specifically include an increased emphasis on complex scenario development to better understand potential outcomes from poorly understood risk environments [**75**]. The benefits of added scenario planning allow for the exploration of "what if" events, in order to better understand the trajectories of catastrophic risk pathways well in advance. Based on the outcomes of these scenario planning exercises, governance strategies can be developed that better address these risks appropriately and proactively, whether it is to increase research on the emerging risk, to focus on precautionary measures to avoid worst case scenarios, to modify the risk appetite, or other options. So far, this extended framework has seen some exploration for solar radiation management approaches toward geoengineering, but further application within the Arctic, and the area of sea-ice based geoengineering efforts, could help to inform the specific planning needs of Arctic nations and stakeholders when addressing geoengineering-based risks [**76**]. In the case of regional opposition, as mentioned earlier regarding tests on current technologies, the risk governance approach encourages early inclusion and understanding of stakeholder concerns to better develop approaches that may reduce conflict or identify areas needing greater cooperative engagement early on in the pre-analysis phases, by considering value perspectives that may lead to disagreements later. Additionally, the merging of risk governance with approaches outlined in securitization theory may offer a greater and more comprehensive look at the potential for both domestic and international risk that is presented through this emerging set of technologies, as they pose potential challenges at all levels of analysis [**77**].

3.8 Conclusions

The rapid decline of sea ice, combined with increased interest in the Arctic, is pushing nation states and independent actors in the direction of action to protect and preserve Arctic ecosystems. With advances in technology and proposed solutions, it is increasingly likely that these actors will make use of geoengineering solutions to help curb the losses of sea ice and protect national interests. This is not to say that the efforts themselves should be avoided, but that they must be done with a level of care and precaution, in order to avoid or minimize the negative consequences. The current lack of global action to curb emissions may spur these groups to act independently when combined with an increasing number of extreme events due to climate change. Without robust frameworks and agreements in place to promote careful action, or to consider unintended consequences toward other stakeholders in the region, these geoengineering efforts have the potential to trigger geopolitical disagreements or conflicts, as disagreements arise about best practices or which area receives disproportionate impacts from these efforts. The Arctic is uniquely positioned to develop and implement many of these agreements prior to the impacts of geoengineering efforts being felt. As a result, it is imperative that nation states and international bodies across the Arctic begin work toward a unified approach to these solutions, in order to help protect individual interests, but also to promote a safe and responsible path towards addressing this challenging problem. Recently evolving frameworks in risk governance are well suited to guide the kinds of challenges geoengineering presents, but they may do so more effectively if adopted earlier on in the process. By working to advance international frameworks focused on identifying the consequences of potential decision pathways sooner, and by focusing on the inclusion of those groups affected by the consequences of proposed measures, it will allow for the safer exploration of proposed interventions through collaborative mechanisms.

3.9 Author Contributions

Conceptualization, A.P.B., T.J.B. and U.S.B.; Writing lead, A.P.B.; Writing—review and editing, A.P.B., T.J.B. and U.S.B., T.J.B. All authors have read and agreed to the published version of the manuscript.

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3.11 Institutional Review Board Statement

Not applicable.

3.12 Informed Consent Statement

Not applicable.

3.13 Data Availability Statement

Not applicable.

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3.15 Conflicts of Interest

The authors declare no conflict of interest.

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Chapter 4: Security Tipping Points: A Measure of Securitization

4.1 Abstract

The growth of cascading and compounding risk requires a broader and more comprehensive understanding of the challenges generated by a global world. The interconnectedness of climate related challenges prompts a need for a more comprehensive approach toward understanding climate security, and security in general. This paper addresses this growing need, through the introduction of a conceptual model to assess catastrophic risks that endanger the survival of individuals, nations, regions, and international communities. Through the development of a more comprehensive risk formula, and the connection to a visual conceptual model on instability, this approach offers security analysts and risk experts a new tool to understanding catastrophic risk. This paper explores the connections to just securitization and "real" risks, compares the use of analytical risk formulas in different fields, and proposes a new approach toward the assessment of disruptive events, destabilizing events, and the extent to which internal and external capacity can help to reduce the associated impacts. The result of this work provides a common perspective that allows for assessment at all-scales, and all sources of insecurity, to provide a shared dialogue across fields of study that pertain to security, whether human, national, environmental, climate, or other.

Keywords: securitization theory, just securitization, climate change, catastrophic risk, disruptive events, destabilizing events, capacity, natural hazards, conflict

4.2 Introduction

While there is growing recognition that issues of international security and disasters present complex and interconnected challenges in governance and risk approaches, there are few mechanisms or tools in place to identify and assess associated risks within a common framework. Catastrophic risks, or events that may lead to destabilization or systemic failure, are particularly challenging to address. This is being amplified by climate change, as geopolitical risks and geophysical risks become increasingly compounded. When it comes to climate-related catastrophic events, however, there are significant challenges emerging in identifying their future potential.[1] This difficulty in identifying points of failure or threats to survival is, in part, because there is a high degree of uncertainty associated with human decision-making, as well as the potential for unintended consequences in system response. However, the ability to identify when a threat or hazard poses a "legitimate" or "semi-objective" risk to the survival of a referent is essential in understanding when security related efforts may be seen as justified both by security actors and their audiences. The conceptual framework proposed here is intended to address that important gap, to provide a mechanism for evaluation of risk, as it relates to the security or survival of a referent of analysis.

The magnitude of modern risks, from global pandemics to climate change, produce the potential for impacts at all levels of human society and across multiple dimensions but are often evaluated through incompatible means, or in an isolated environment, where risks are not linked. To some extent, this has to do with the scale at which these fields tend to operate. Within disaster studies, it is not uncommon for the issue to be framed as "all disasters are local."[2] In international security studies,[3] the focus is often on the interaction between states or regional governance bodies, or it is framed as something that exists at global levels, and rarely are domestic issues considered. However, there are clear linkages connecting the two scales. Disasters have been shown to weaken state or regional governance structures,[4] while conflict has certainly been shown to have negative impacts at the individual and local scale. Over time, these fields have begun to broaden their scope, as international security studies have widened the focus from political and military analyses to include environmental, societal, economic, and other sectors, while also deepening that focus to the human level as opposed to primarily focusing on national and higher levels of analysis. Similarly, the broad field of disaster studies has increasingly recognized the effects on human populations due to conflict, as well as the potential for conflict to be generated or amplified by disaster related impacts. Despite this, few tools exist that allow for assessment of security from a unified perspective.

Through a critical review of literature, and methodological analysis of existing risk formulas and functions, this paper introduces a new conceptual framework, built on evolving advances and dialogues in security and risk studies, to better understand the extent to which disruptive events have the potential to lead to the instability of a referent through the exceedance of capacity. As primary components, this model uses perspectives from infrastructure risk analysis, disaster risk studies, and conflict studies to explore overall capacity when compared with specific disruptive events, and the potential for a referent to become more stable, or less stable, in the face of those disruptive events. In this way, it provides a new perspective that accounts for the unique complexities between events and capacity and allows for varying degrees of complexity to be explored within the system, at differing levels of analysis. Additionally, through this approach, it is also possible to conceptualize change through time, as well as the stabilizing (or destabilizing) effects of external capacity.

4.3 Connections to Securitization Theory

This conceptual model relies not only on the understanding of measurable risk but also the connections to risk as a semi-subjective discourse. A foundational aspect of this work is connected to international security frameworks that recognize the securitization of a particular threat or hazard.[5] Traditionally, security as a field of study was primarily concerned with political and military threats to nation-states, but a level of security has long been difficult to define. A foundational, yet often overlooked, definition within the study of national security originated with Walter Lippmann in 1943, as the idea that "a nation has security when it does not have to sacrifice its legitimate interests to avoid war, and is able, if challenged, to maintain them by war."[6] Arnold Wolfers later paraphrased this argument in 1952 as "a nation is secure to the extent to which it is not in danger of having to sacrifice core values, if it wishes to avoid war, and is able, if challenged, to maintain them by victory in such a war."[7] Wolfers expanded on this, by exploring security and insecurity as having the potential to be both objective and subjective, whether dealing with the absence of a threat, or the absence of fear of a threat. The underpinnings of these arguments have continued to shape modern exploration of international security studies.

Throughout the late Cold War period and into the 1990s,[5,8–11] it became a point of focus that traditional approaches toward security were perhaps too heavily focused on political and military security and that such a focus was insufficient to address the potential challenges faced by people, nations, and regions. This led to the broadening and deepening of security studies through the emergence of several new concepts and frameworks, to include human security,[11] environmental security,[9] and securitization theory.[5] *Security: A New Framework for Analysis* established a framework for assessing the process by which a particular issue was pushed beyond the political to become an issue of security, rather than past attempts at defining a normative or measurable state of being for security or insecurity.[5] This approach, known as securitization theory (also often referred to as the Copenhagen School of security studies based on its origins), expanded the ideas of security as a subjective process, through which a securitizing actor elevates an existential threat through a speech act, through the acceptance of an audience, which justifies extreme measures, or the breaking of norms. This is premised on the idea that a threat is posed as endangering the very survival of the referent that needs protection. The initial framework argued that, in almost all cases, this process of bypassing or moving beyond the political in favor of security is a negative one.

Despite the emphasis on the subjective nature of risks outlined over decades of international security dialogues, there is also recognition among scholars that some events have the potential to constitute real and objective risks to a referent's survival, and therefore may be seen to justify the securitization of a risk and protection of a referent. In *Security and the Environment* (2010), Rita Floyd argued that it may be possible to securitize a threat for moral reasons, particularly as it pertains to the environment, when focused on humans as the referent.[12] Later, in 2019, Floyd went on to refine this approach and developed *Just Securitization Theory* (2019), which outlines the potential for a threat to be securitized for "just" reasons, based on the perspectives and intentions of the actors involved.[13] Floyd lays out a set of criteria required in order to consider a securitization to be "just," which includes 1.) Just Reason (or threat), 2.) Just Referent (worthy of protection), 3.) Right Intention, 4.) Proportionality (of expected good), and 5.) Chance of Success (of securitizing). Floyd extended this to also assess whether measures carried out under a successful securitization could also be considered just, based on 6.) Proportionality (of measures), 7.) Necessity (of measures), and 8.) Discrimination. It is the first criterion, Just Reason, which is primarily explored within this paper. Just Reason states that "an objective existential threat to a referent object, that is to say a danger that – with a sufficiently high probability – threatens the survival or the essential character/properties of either a political or social order, an ecosystem, a non-human species, or individuals."[14] However, this poses a challenge, in that the determination of an objective risk or threat to a referent is often dependent on highly subjective means. Therefore, a major aspect of this paper, and the utility of the proposed conceptual model, is to assist in the determination of an objective risk, to better answer the question of when that threshold is approached or crossed.

In addition to that focus, this framework addresses another expansion that has been proposed to securitization, which is the shift from an active threat focus to the recognition of the potential for both direct causes, as well as constitutive causes that generate securitization. This was formulated in 2012 as the idea of riskification, or the elevation of priority of a potential risk or harm, being another parallel to securitization, where and was driven directly by the increasing need to address climate change related issues as a different way of framing security concerns.[15] This concept was further expanded as a threatification-riskification duality under a common securitization perspective, as outlined in the Securitisation of Climate Change (2016).[16] This approach recognizes that risks may arise in both passive and active situations, modifying both long term and short term shifts in measures to address severe concerns. Floyd (2019), similarly framed this in the context of agent-caused and agent-intended, to represent active, and agent-lacking, which aligns with passive risks.[13] This parallels ideas in disaster studies, aside from specific terminology, where intentional actions (e.g., military invasion, terrorism, etc.) remain classified as threats, while conditions that contribute to harm (e.g., earthquakes or floods) are classified as hazards. In risk management approaches, explored in the next section of this paper, these classifications of threats and hazards are often distinguished as a sub-component of risk, and not as risk being parallel to threat, generating a terminological mismatch. For the purposes of this framework, it would perhaps be more appropriate to identify "hazardification" as a new and relevant term to both distinguish from "threatification" in the security world but maintain compatibility within disaster studies. The next section of this paper will explore approaches to merge these ideas existing within risk functions and equations into a combined approach that should align with both security and disaster concepts for addressing these challenges.

4.4 Convergence: Risk Analysis in Disaster, Infrastructure, and Conflict Studies

The terminology and perspectives between the fields of disaster and security studies do not readily provide a common framework for analysis. In some cases, they may even be framed in an exclusionary way, such as where UN definitions of hazards explicitly avoid the inclusion of armed conflict as a potential hazard, despite recognizing the presence of anthropogenic hazards.[17] Instead, armed conflict is often viewed through separate frameworks entirely. Global interconnections, both horizontally (between states, communities, firms, or other units of analysis) and vertically (at different levels of analysis, whether broader levels of governance within the nation or external to it) are becoming increasingly blurred as supply chains and logistics networks become critically intertwined. Due to current and projected changes to climate related hazards, increasing concerns about energy security, economic interdependencies, and other drivers, it is increasingly necessary to explore both disaster and security challenges from unified perspectives.

The approach toward probabilistic risk has evolved independently in a number of fields to represent the concerns that have often been seen as most pressing within those fields. Analyses of infrastructure and more recently cybersecurity risk tend to emphasize risk as it relates to specific assets. Disaster risk related studies often focus on the impacts of natural hazards and the total exposure of assets and people in the impact area. In conflict studies, risk is often seen through the lens of whether or not a conflict is likely to occur, and the potential intensity of that conflict. As each of these fields analyzes risk from slightly different perspectives, each has explored different ways of assessing those risks. For the purposes of this framework, it is important to identify a common understanding of risk as it pertains to the individual, local area, state, nation, or other referent object being analyzed. Through a unified approach, it also allows a more complete perspective on risk, and risk over time. First, major domains of risk analysis will be identified as they relate to this framework, deriving lessons from infrastructure analysis, disaster risk studies, and conflict studies. This will be followed by a more comprehensive approach in order to propose a method that accounts for the complex and compound interaction between these individual fields.

4.4.1 Infrastructure Risk

Popular modern approaches to calculating risk relating to infrastructure-based assets gained prominence through work within the field of nuclear infrastructure risk analysis, with an effort led by Norman Rasmussen to assess the possibility of risk associated with the failure of nuclear power based generation systems.[18] While the approach had been pioneered within National Aeronautics and Space Administration (NASA), it had been abandoned in favor of other tools at the time.[19] For Rasmussen, the challenge was a need to better understand the potential risk of a nuclear reactor failure incident at not just one location, but at a range of locations over time. This led to the use of a tool known as probabilistic risk analysis (PRA), which was clarified and refined in his application, and became the basis for numerous risk analysis approaches that have spawned since.[20] The equation for this approach was represented as $R = F * M$, where a risk (R) was the result of the potential frequency (F) of an event multiplied by the magnitude (M) of the event. This approach provided a way to look at the overall likelihood and impact of an event occurring, and over time evolved into a range of formulas used within risk planning fields. Early on, Rasmussen was careful to clarify terminology, in that any particular "hazard expresses the potential for producing an undesired consequence without regard to how likely such a consequence is."[20] The PRA approach included events of both human and natural origins, so there was no need to limit the equation to one category of events. The magnitude of the hazard, and the frequency of the hazard, then became the main drivers of risk. The same components can then be applied to a range of event types, and the total risk can be evaluated as a risk integral to account for a combined probability of multiple risks occurring.[21]

Kaplan and Garrick (1981) expanded this line of reasoning beyond a single probability and consequence to include the idea that the overall combination of events (scenarios), their consequences, and their probability combine to represent more holistic risk.[22] Since those early efforts, similar approaches have persisted in the world of infrastructure threat and hazard analysis, with modern formulas commonly reflecting the overall risk to an individual asset as something similar to $R = (T \times V \times A)$, where T represents the threat being assessed, V represents vulnerabilities that allow the threat or hazard to damage or disrupt the asset, and A represents an asset of value.[23] This may also involve countermeasures or controls (C) which represent the controls (technical, operational, or management) that are employed to reduce the risk to the asset.[24] Other approaches represent the risk (R) as a function of threats (T), vulnerabilities (V), and consequences (C), as $R = f(T, V, C)$.[25] These approaches are often applied to both physical assets and infrastructure as well as cyber related systems. In some cases, this may include the potential for cascades of risk or networked risk due to a key asset failing, leading to the failure of dependent assets. Power distribution systems offer a common example of this, where loss of a power supply results in failure of dependent infrastructure, which may in turn suffer catastrophic failure from fluctuations to pressure, heat, etc.

4.4.2 Disaster Risk Studies

Within disaster studies, a high emphasis is often placed on natural hazards, while technological or human caused events are more often relegated to the security world. However, this often ignores the exploration of NaTech incidents, or combined risk events, which are an area of growing concern.[26] In some cases conflict events are specifically excluded from disaster frameworks, despite increasing connections between disaster risk reduction and conflict reduction efforts. Additionally, these types of events are increasingly more likely as a combination of increased hazards from climate change and amplified exposure amplify risks. These mixed efforts may stem from a lack of a clear path for merging or holistically understanding the risks associated with compound (multiple cause) or cascading (chained impact) events, but also stem from differences in responsibilities between actors, or challenges in unifying efforts around political drivers.

To better understand the risk potential of disasters, a pseudo equation is often used to represent overall risk to a set of assets or a group of people, based on natural hazards. Initially proposed in 1994, this equation framed the risk of a disaster as R = H x V, to represent risks (R), hazards (H), and vulnerability (V) that might be seen to amplify the hazards.[27] Exposure (both spatial and temporal) was proposed as another component to understanding risk based on early work from the United Nations Disaster Relief Coordinator (UNDRO),[28] as a subcomponent of vulnerability or hazards,[29] and from recommendations coming from lessons in the insurance industry.[30] Eventually, exposure (E) became a top level variable in some versions of the risk formula, used as a direct modifier to the other two components.[31,32] This led to the proposed formulation of disaster risk as R = H x E x V.[33]

Some have extended this advance even further with the inclusion of Coping Capacity, represented by C to measure a reduction of risk or alternatively as a resilience factor. Combined, this equation helped represent a simplified conceptual understanding of natural hazard driven disaster risk, as well as potential mechanisms to limit or constrain that risk, and appears as R = (H x E x V) / C.[34] However, conflict and security related concerns surrounding active or intentional threats are not typically considered as part of this formula, with some definitions explicitly indicating that conflict is excluded from disaster based approaches on hazards.[35] Additionally, in connection to resilience and sustainability efforts, capacity is often used to refer to resource capabilities, and to a lesser extent is also combined with adaptive capacity,[36] to highlight the potential for a particular system to learn from the event to recover more effectively. Based on that context, limiting capacity to coping capacity is insufficient to represent the long-term survivability of a referent.

Modifications to the disaster risk-based formulas vary substantially and may also separate individual capacity from large scale mitigation efforts, as is the case with DR = H x [(V/C)-M].[37] This equation assumes magnitude, probability, duration, and extent to be a subcomponent of the hazard (H) itself. It would also require the assumption that large-scale mitigation can substantially reduce or negate entirely issues of personal vulnerability and capacity if mitigation efforts are significant enough. In most cases, this would likely be the case for specific disasters, but may still allow for individual vulnerability to persist which poses greater challenges in the face of localized or alternate forms of threats and hazards. Therefore, the ability to withstand events may require a combination of personal and societal risk reduction efforts for broader applicability beyond disaster events. As an example, the mitigation of a large-scale disaster may sometimes reduce risk for a locality, but increase risk for individuals within an area, such as through the diversion of flood waters to limit population impacts. In this way, mitigation efforts for a community may increase risk for certain members of the population.

4.4.3 Conflict Studies

Approaches to probabilistic risk analysis have also been employed to better understand conflict studies and conflict potential, to varying degrees of success. Within this area, the calculation of risk is often focused on the probability of a conflict occurring,[38] the potential occurrence and intensity of a conflict,[39] and in some cases the potential of a successful conflict.[40] This may also be scaled to the level of terrorism-related events, exploring the probability of an event, the probability of success, and the potential consequences of that event.[41] Additional studies have explored the probable potential for the escalation or reduction in conflict over time.[42] However, measurements of the impacts of those attacks are often less explored. In cases of probability of occurrence, the range of formulas vary substantially, and few deal with the direct impacts to a referent outside of military forces. Recent approaches have attempted to assign metrics to components like combat power, which is described as the "total means of destructive, constructive, and information capabilities that a military unit or formation can apply at a given time,"[43] and may appear as f(Combat Power) = (Intelligence x Physical Elements) / Command & Control, where Command & Control may reduce effectiveness through bureaucratic impedance, or improve it through exceptional efficiency.[44] This provides an interesting dimension to the active or intentional threat aspect of this framework, because it provides a measure of the destructive capabilities of a particular threat, in similar ways to that of a hurricane category, or earthquake magnitude. While humans may be less predictable than hazards in carrying out an attack, the need for evaluating the potential of that attack as a disruptive event persists.

The ability of a referent to withstand conflict has been explored as well, as internal conflict, external conflict, or a combination of the two. This is often framed in terms of capacity or capabilities, whether in terms of state capacity or conflict capacity, but the dependent factors may vary substantially. Internal conflict-carrying capacity has been framed in terms of contentiousness, state repressiveness, and the presence of violence/contention as "the ability of the state to regulate intense internal conflict without loss of system integrity,"[45] while state capacity itself, in relation to both internal and external conflict, has been connected as a combination of the presence of conflicts, controls, GDP per capita, an index of democracy and other factors.[46] Analysis of significant drops in state capacity have also shown that conflict occurrence may be related to the strength of states prior to the loss of capacity.[47] Taken together, conflict has the potential to affect dimensions of threats, exposure, vulnerabilities, and capacity.

4.4.4 A Combined Risk Function

Based on a combined examination of the fields, it is necessary to reassess a more unified version of the risk formula to address the combined complexities of threats and hazards, not only to human and national security, but other levels and dimensions of security as well. For the purposes of this framework the calculation of risk will be in the form of a function, rather than an equation, as the calculation of risk does not fully support transposition of the variables (i.e., it is not actually possible to derive H as R / V in earlier formulas, but instead, R is a function of H x V in more traditional approaches). This is seen as an important clarification, as the potential for a hazard to exist is not necessarily dependent on the other variables, but rather it is the impact that is dependent on the complex interactions between those variables. The representation as a function recognizes that risk is the output of the calculation, and while the variables are dependent on one another, that relationship is not always able to be easily isolated. For the purposes of this framework, the risk of a disruptive event leading to instability (R_I) is defined as a function of magnitude (M), exposure (E), vulnerability (V), and capacity (C), which can be seen in Figure 4.1. This approach offers a summarized starting point, to quickly evaluate the potential risk of instability based on a disruptive event, and capacity of a referent.

$$R_I = f(M, E, V, C) = \frac{M \times E \times V}{C}$$

Figure 4.1: Simplified Risk Function

Simplified, merged risk function, representing magnitude (M), exposure (E), vulnerability (V), and total capacity (C).

When exploring each primary variable, it is important to recognize that there are important subcomponents to each. The magnitude (or severity) of the event measures the total potential impact (not necessarily realized impact) for damage or disruption to existing human, social, or built systems. This includes both threats and hazards within a unified variable, while subcomponent magnitudes may be represented by the sum of M_t and M_h respectively. By combining both components into magnitude, it allows for the recognition that disruptive events are often of compound or complex origins, particularly when exploring the stability at the level of nations, and that either or both may contribute significantly to instability. Additionally, it recognizes that the ability for one event to trigger another through cascading risk is possible. For quantification purposes, it can be viewed as having a range from 0 to nearly infinite, although practically it would reach a limit on the order of an existential risk (or a potential civilization ending event). The exposure to a disruptive event represents the combination of both spatial and temporal exposure of people and assets (to include infrastructure), and may be further broken down as E_s and E_t, respectively, to represent those dimensions. Within exposure, the intersection of an event between people or assets can be measured on a range of 0 to 100 percent spatial and temporal co-existence during the analysis window. The vulnerability component, or V, represents weaknesses within existing social or physical structures that allow for the disruptive event to impact existing systems, and may be measured as little to no vulnerability at zero, up to near complete vulnerability of systems, based on the event being assessed. Breaking these components up in this way indicates that each one has the potential to independently nullify risk if they are brought to zero.

Finally, the capacity represents the combined resources and capabilities, or ability and willingness to reduce, withstand, or avoid the impacts associated with the disruptive event. In some perspectives this may be seen as "the other side of vulnerability."[48] However, it is insufficient to combine the two since capacity as a denominator recognizes that capacity can be overwhelmed, which indicates the potential for a tipping point or instability in the system to arise. This component variable may be further expanded to include coping capacity (C_c) as the ability to withstand events, and adaptive capacity (C_a) as the ability to adapt to the disruptive event and lessen the impacts over time. The total capacity of a nation, for example, may include fiscal capabilities, infrastructure, military, natural resources, social cohesion, and more, while the total capacity of an individual is likely to be far more limited. Capacity may also include the potential for external capacity (capacity that is not internal to the system being assessed) to temporarily support the system and prevent exceedance. As a result, capacity can scale substantially from local to international levels, with the potential for substantial external support, and could be measured from nearly zero, up to the entire capacity of global civilization, as a theoretical upper limit.

The intention of advancing and expanding this function, as well as to attach greater attempts to assign measurements to each component, is to support efforts to greater quantify these risks going forward, which provides several benefits when it comes to the feasibility and plausibility of risk outcomes. A modified version of this can be seen in Figure 4.2. When assessed quantitatively, even if derived by subjective means, this function produces a ratio where values greater than 1 indicate significant risk to a referent, while values less than 1 are more likely to indicate the stability of the system against a particular disruptive event.

$$R_I = f(M, E, V, C) = \frac{(M_t + M_h) \times (E_s \times E_t) \times V}{(C_c + C_a)}$$

Figure 4.2: Expanded Risk Function

Expanded risk function, representing threat magnitude (M_t), hazard magnitude (M_h), spatial exposure (E_s), temporal exposure (E_t), vulnerability (V), coping capacity (C_c), and adaptive capacity (C_a)

Beyond this approach, it is possible to further expand and break down the subcomponents, if necessary for specific cases. When exploring the vulnerability of a nation-state, for example, added analysis could also account for dimensions like human vulnerability, physical infrastructure vulnerability, or social system vulnerability. Coping capacity could involve both engineered and social structures currently in place, and adaptive capacity could involve a range of social agreements, community cohesion, etc. Additionally, within and across units, it may be necessary to further address complex interdependencies that may amplify or dampen subcomponents. However, because of these differences, more specific variables would likely differ between levels of analysis and units of analysis and would require different formulas or equations for each assessment being performed. Therefore, the function as proposed is intended to span these levels and approaches toward analysis to provide both consistency and flexibility.

4.5 Key Definitions

In order to standardize the approach within this framework, key terms have been identified as they relate to existing definitions where possible to better reflect the state of each contributing field, but aligned to be consistent with the framework where necessary. However, due to the broad nature of these terms, they also provide flexibility for the examination of a wide range of factors that may make up components of these definitions.

Term	***Definition***
Adaptive Capacity	The ability of a referent to adapt or shift strategies in the face of a *disruptive event*. May be a product of social cohesion, governance capacity, robust interconnectedness, etc., and will vary substantially at different scales or levels.
Capacity	The combination of all the strengths, attributes and resources available within an organization, community or society to manage and reduce disaster risks and strengthen resilience.[35*] Within this framework, this refers to the sum of both *adaptive capacity* and *coping capacity*.[36]
Coping Capacity	The coping capacity is the tangible and intangible resources of the referent or state to withstand, resist, or recover from a *disruptive event* effectively.
Destabilizing Event	A destabilizing event is a more extreme version of a disruptive event, where the impacts of the event outpace capacity, or the combined *coping capacity* and *adaptive capacity*, and place the object of analysis at severe risk of failure.
Disruptive Event	Natural or human caused events that affect the extended operability of the organization or unit of analysis. These may be viewed as either threats or hazards.[49**]

Exposure	The extent to which people, infrastructure, or other human systems are subject to the presence of a *threat* or *hazard*, primarily with regard to spatial and temporal dimensions.
Hazard	A process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation.[17*]
Magnitude	The potential peak disruptive power or severity of a *hazard* or *threat*. Examples may include a hurricane category, earthquake magnitude, total combat power of an opposing force, etc. Only fully realized through *exposure* and *vulnerability* to that threat.
Referent	The focal object of analysis that is intended to be protected, sometimes referred to as the unit of analysis. The term *referent*, or *referent object*, is used here in line with the Copenhagen School's usage, and to avoid ambiguity when discussing the Unit level.
Threat	Actor(s) with capability and intent, or an event with potential capability, to significantly harm security interests.[50**]
Unit of Analysis	The unit (an individual, subunit, unit, international, or system) being analyzed. Typically refers to a specific unit, rather than a general level of analysis.
Vulnerability	The conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of *hazards*.[51*]

* = Direct from source, ** = Inspired by source

Table 1: Definitions

4.6 Framework Core

The current focus of this framework is to apply a conceptual, and currently largely qualitative, approach to better understand the potential for a referent object to face disruption or destabilization because of a disruptive event. As explored in prior securitization frameworks, while some factors are not easily quantified, “they can all be meaningfully conceived in terms of scales, and principled reasoning can lead to meaningful depictions.”[52] To frame this effectively a model of a trapezoid is used, where the base represents overall capacity, and the top represents the magnitude, exposure, and vulnerability associated with a disruptive event or set of events. This closely matches a number of the risk formulas explored in **Section 4.3**, where the numerator represents the impacts of an event, while the denominator represents the ability to withstand that event. Additionally, the shape of a trapezoid can very easily visualize the stability of a system in the face of an event (a wider base than top is more stable) versus the instability of a system (a wider top than base is more unstable). In most situations, the capacity of a nation-state will be sufficient to withstand and recover from a wide range of disruptive events. However, in situations where that disruptive event or series of events outweighs the overall capacity of the nation-state, a situation occurs where that system becomes unstable and the potential for destabilization exists. The greater the ratio of the disruptive event to the available capacity, the higher the likelihood of a systemic failure of that referent. This concept can be seen in Figure 4.3. In situations where the product of disruptive events exceed capacity for an extended period, the likelihood of that failure becomes substantial unless otherwise supplemented by external capacity (i.e., the assistance of other states). Based on the diagram, the potential for the system to reach a tipping point becomes clearer, until a point where it may enter into irreversible change, to include weakening, failure, or total collapse, at which point the extremely top-heavy trapezoid may metaphorically fall over.

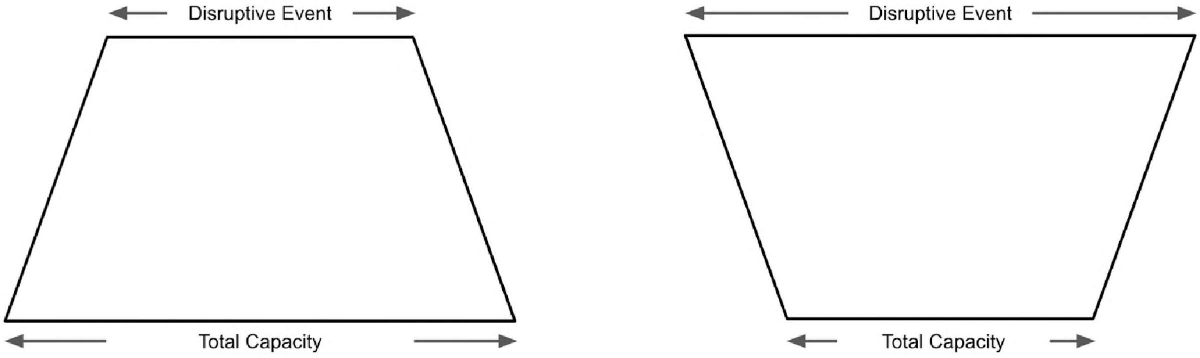

Figure 4.3: Security Tipping Points Conceptual Model

Example showing a simplified version of two different possible combinations under the framework, one (left) indicating a unit of analysis that is stable against a potential disruptive event, and the second (right) showing a unit of analysis that is unstable against a disruptive event.

Similar explorations of tipping points exist in both natural and social systems, where thresholds indicate that the behavior of a system changes rapidly, rather than linearly, and may enter a new permanent state of existence. Within this framework, that point becomes a point of instability, where the *referent* has the potential to substantially weaken or fail if the event is prolonged, if capacity cannot be expanded (either internally or externally), or if additional events compound the original event. Past theories in ecological studies,[53–55] as well as mathematical theories on catastrophe theory (not directly related to disaster related catastrophe studies, although a fitting connection),[56] provide insights into rapid and dramatic change-of-state potential for natural systems, whereby they fundamentally differ from their previous system state. This approach allows us to conceptualize events, or a series of events, that pose a significant risk for the referent, and therefore may justify further measures to stabilize the system, to prevent failure. From a securitization theory perspective, these may constitute a call for extreme measures.

The steps to employing the framework are basic but provide the ability to expand the framework to substantially more complex scenarios. Initially, it requires an identification of a referent, an event, and the overall capacity of each *referent* being analyzed. Similar work on fragile state indices or governance risk indices may provide good insights here as to the total capacity of a particular nation, for example. The multi-sector approach, as outlined in previous sections and connected to securitization theory, provides a dynamic approach and recognizes that a combination of sectotal capacity may provide flexibility in analyses as well. This series of steps begins with a simplified approach: 1.) identify a referent of interest, 2.) identify the potential of a disruptive event (either through past events, modeled events, or other approaches such as downward counterfactuals), and the exposure and vulnerability associated with that event, 3.) identify the internal capacity of a referent object, 4.) evaluate the ability of the referent object to maintain stability. Further exploration may optionally involve 5.) an iterative approach toward changes in capacity (either internal or external), or the introduction of additional events (either cascading, concurrent, etc.). This will now be explored in greater depth.

1) **Identify a referent of interest**. This may exist at any level of analysis, across different sectors of analysis.
2) **Identify the potential of a Disruptive Event** (2 parts):
    a) Identify a disruptive event itself. In some ways this provides a more straightforward process, identifying a specific natural event (eg., a magnitude 8.0 earthquake, a Category 5 hurricane, a specific military invasion of known combat power, an economic downturn, etc.).
    b) Based on that event, identify the exposure of the referent (spatial overlap or proximity, temporally, and potentially proportionally), and the vulnerability the referent has toward this specified event.
3) **Identify the Capacity available to protect that referent**. The capacity of a referent object includes a complex set of factors that are often interlinked, and can span a range of sectors. This may involve military, political, environmental, societal, and economic dimensions, as well as those from other perspectives on security. Initial assessments allow for setting a baseline, and may be further adjusted through iterative analysis.
4) **Evaluate the overall ability of the referent object to maintain stability** and withstand the potential impact from the event in question. If the event is seen as sufficient to destabilize the referent object, then it may go beyond a disruptive event and become a destabilizing event.
5) Optional: Iterate on the scale of the event, additional events, or additional capacity over time (shown in greater detail). Through a multi-staged process this can highlight either greater levels of instability, or potential routes of re-establishing or promoting necessary capacity.

This can be represented visually as a trapezoid in most cases, to indicate the level of stability or instability within the system. When the top of the trapezoid, representing a disruptive event's potential, is smaller than the bottom of the trapezoid, representing capacity, the referent is considered more stable or secure against that disruptive event (Figure 4.3). When the top of the trapezoid is larger than the base, indicating the disruptive event exceeds the coping capacity in the system, the state is unstable (Figure 4.3). At the most extreme levels, the trapezoid may reach that of a triangle, in a situation where the probability of failure is either 0 percent or 100 percent. While that probability of a disruptive event having 0 percent impact may be unlikely, there are a vast number of examples where that probability is so low as to equate to zero. For that failure rate to reach 100 percent, however, the failure of the referent is likely to be guaranteed. Most situations will fall somewhere in between, because despite failure being very likely, there are numerous examples where a referent may recover from otherwise disastrous circumstances. The key here is that once the stability of the system comes into question, the justification or semi-objective status of a threat or hazard being "legitimate" is confirmed, and it does not require absolute failure to constitute legitimacy of a risk.

4.6.1 Levels of Analysis

One of the challenges in analyzing the potential for failure of a referent is that the capacity, in terms of both coping capacity or resources, as well as adaptive capacity, also vary substantially, and stability is not always improved based on scale. As a more extreme example toward this, there are countless examples of individual people surviving extreme events, despite local governments being overwhelmed, and other individuals being overcome by that event. However, when aggregated across the number of individuals facing risks, we may expect that to be less consistent across large numbers. In many cases, for example, an individual facing the same event as a locality is likely to be substantially more at risk than the locality as a whole (see Figure 4.4).

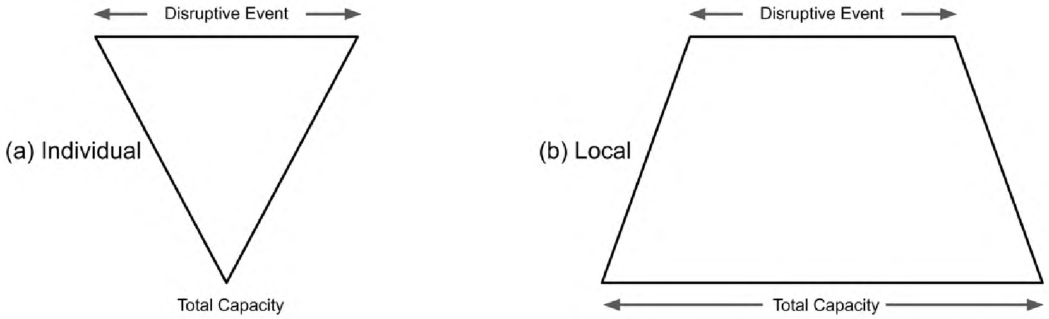

Figure 4.4: Comparing capacity

Highlighting the overwhelming risk a disruptive event may pose to individuals (a), and the potentially lower risk that same event may pose to a local system (b).

The ability to assess risks at different scales, however, provides significant utility in spanning different referents, levels of analysis, etc. Additionally, this supports the ability for comparing between scales, and viewing situations where the sum of the parts may be different than the individual components, such as may be the case in national versus local comparisons. Therefore, this flexibility supports the ability of analysis of security and disaster concerns in a unified context, where the disruptive events and capacity may vary substantially, despite large scale impacts. Analyzing the same event through different lenses provides insights as to where component pieces may face issues of survival, where the larger system may maintain stability.

4.6.2 Change Over Time

As risk is not static, it is important to have mechanisms in place to evaluate changes to risk over time. This conceptual model supports this approach through the visual representation of change, as differences in risk between time steps, where events or capacity may increase or decrease between time frames, highlighting important system changes. An example can be seen in Figure 4.5. When representing a large number of time steps, the visual tool approach may become challenging, but a table, or plot, of the direct ratio of risk over time or the result of the risk function would still provide utility to indicate a system change toward instability (e.g., $t_0 = 0.8$, $t_1 = 0.95$, $t_2 = 1.1$). In the case of collaborative assessments, either approach could be used, but the visual approach, as shown, offers clarity as to the changes of risk.

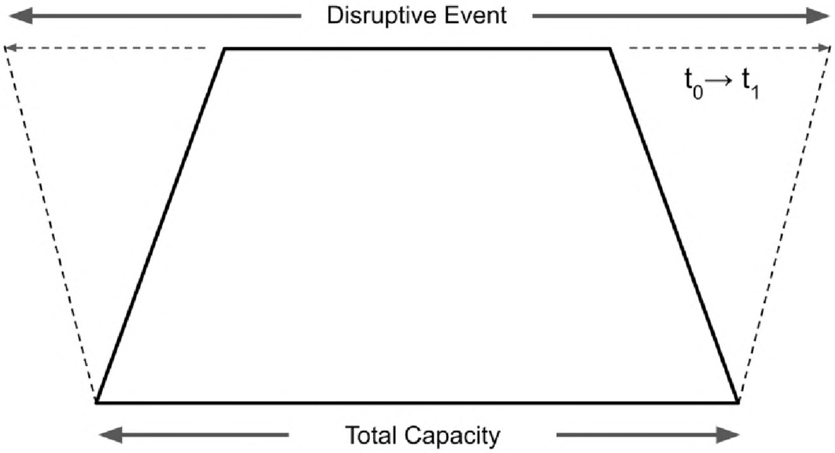

Figure 4.5: Risk over time

The risk of a system show increasing between two time steps of analysis, represented as $t_0 \rightarrow t_1$, where the impact of the disruptive event has expanded between time steps, while the total capacity remains the same.

4.6.3 Inflection Points

Another key benefit to this model, especially if assessed over time, is the ability to understand the point at which a referent becomes unstable, which can be seen in Figure 4.6. This can occur due to expansion of the disruptive event, a reduction in overall capacity to protect the referent, or both. This is often the case with real-world events, where conditions change over time, and neither the impact of an event, nor the capacity to withstand it, tend to be fixed in place. Within this conceptual model, this aspect provides analysts the ability to explore time more dynamically and can also be used as a way to scale events or capacity until a point of instability is reached. This latter potential draws on work in the field of downward counterfactuals, to assist in identifying the breaking points of a particular system through the gradual worsening of a particular event.[57]

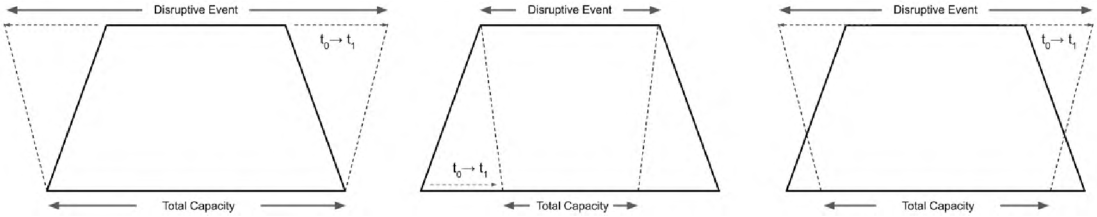

Figure 4.6: Risk Inflection Points

Highlighting changes over time ($t_0 \rightarrow t_1$) to the analysis, where over time the stability of a system may shift. This may be due to increasing impacts of the event (left), decreasing capacity (middle), and both (right).

In the case of an expanding disruptive event, this may occur when the magnitude of an event grows over time, but also provides the ability to assess concurrent or cascading events over time, as one disruptive event leads to another. This can be seen in situations where a regional natural hazard, such as a flood or drought, leads to the potential for conflict. When it comes to projected changes in climate, increased intensity, duration, frequency, and extent of natural hazards is expected to pose previously unexperienced challenges for many regions, highlighting a need to assess these events in tandem with others. Identifying where exacerbating events may occur provides an opportunity to strengthen areas that can be improved through social mechanisms or mitigating structures. Additionally, such events may lead to reductions in capacity over time, as either sustained disruptive events, or other drivers, reduce total capacity without replenishment of resources, shifting the system into one of instability. Complex events may produce both greater or compounded challenges, while reducing capacity, sending an otherwise sustainable and stable system into a state of instability over time. In some instances, this may be bolstered through external capacity. While all the events in Figure 4.6 indicate a higher ratio of risk emerging, the inverse states of each of these could just as easily show a reduction in risk over time as well.

4.6.4 External Capacity

In addition to the total of internal capacity a referent holds, there exists the ability for capacity to be supported through external measures. This may come in two forms: horizontal external capacity (support provided by peer or near peer referent objects), or through vertical external capacity (provided through higher units of analysis within the same structure). This added support is often in the form of temporary measures when coming from a horizontal source (whether a nearby community, or another nation-state) and does not necessarily produce long term capacity for the referent itself (see Figure 4.7). This can provide much needed assistance to sustain through the duration of an event, until recovery is feasible or greater capacity can be promoted internally. However, that external capacity has the potential to diminish during concurrent events, if the supporting unit is unable to continue to provide that support over time or experiences a similarly disruptive event. Lacking that supplemental external capacity, the instability returns. In this way, external capacity is subject to significant variability over time, and may not be depended on for long term stability when facing that particular disruptive event or set of events.

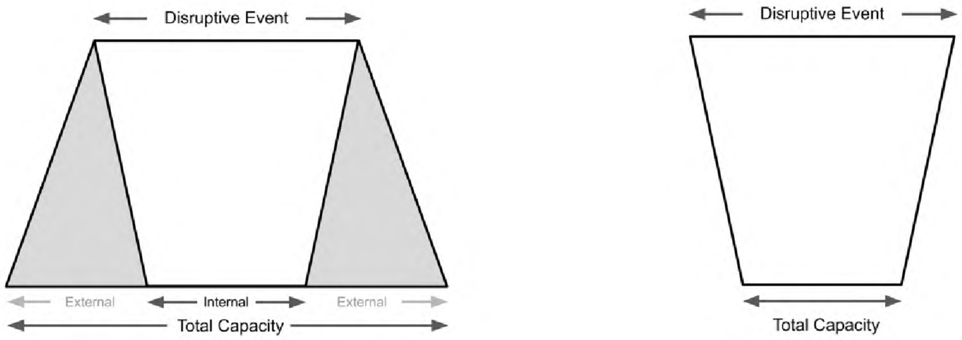

Figure 4.7: External capacity.

Example of an identical disruptive event and identical internal capacity, but with external capacity (left) and without external capacity (right).

Reliance on external capacity for an extended period may result in a loss of that capacity for various reasons. From a military standpoint, for example, horizontal external capacity may be provided through assistance in a conflict through direct intervention, financial resources, through the provision of equipment, or through diplomatic pressures. Any of these options may later be limited by overextension of resources, reductions of fiscal capacity, or diminishment of domestic support within the external capacity provider. From a natural hazards perspective, internal capacity is commonly provided to a referent through higher levels of governance within higher structures like state or national bodies, or through the support of regional mutual aid agreements for multinational partners. It is not at all uncommon for horizontal external support to be offered in such cases as well, where peer nations may provide added aid and resources, until a nation may restore services effectively in affected regions. Lack of that support may result in a critical state of failure for referent's without that support, leading to long term detrimental impacts that have spillover potential. Another factor to consider under broadscale disruptive events, or combined events, is that the available spare capacity of peers may be diminished or limited if capacity is spread over multiple partners or required domestically to respond to internal challenges.

4.7 Example Applications

The most straightforward way to explore the application of this model is through representative examples. In this section, the model will be applied to two sets of disruptive events, with each scenario comparing separate referents or capacity. To illustrate the application of this approach, comparative events have been identified, which offer insights as to the benefits and capabilities of the model. These are specifically not expanded in depth, but rather provide a rapid overview of the potential application of this model from a thought experiment perspective, and can be further explored through expert workshops, quantitative modeling, etc.

4.7.1 Comparative Major Disaster (Island Nation vs. Island Territory)

An illustrative, though brief, example of differences to stability and potential for endangering survival of a referent can be seen in the outcomes of similarly sized hurricanes affecting two islands in the same region, but with differing governance structures, economic capacity, and external capacity. In 2016, Hurricane Matthew made landfall on Haiti as a Category 4 storm.[58] In 2017, Hurricane Maria struck Puerto Rico as a Category 4 storm.[59] Both storms had initially risen to Category 5, before making landfall with reduced speeds. This results in a similar peak magnitude (M_h) for both events. The spatial and temporal exposure of the event (E_s and E_t, respectively) was nearly 100 percent in both locations, based on the total size of area affected, and while located a few hundred miles apart, geographically both locations are within similar regions and climate zones. Preceding these events, however, each site presented very differently in terms of vulnerability and capacity. Haiti had previously experienced a significant 7.0 earthquake on the moment magnitude scale in 2010 and had significant socio-economic vulnerability leading up to the 2016 storm.[60] Puerto Rico, in comparison, has had much higher GDP and economic growth when compared to Haiti over the last several decades.[61]

The most striking difference between these sites is in capacity, and particularly so in respect to coping capacity (C_c). Internally, Haiti's capacity was significantly diminished prior to the 2016 storm. Many sites that were damaged or destroyed as part of the 2010 earthquake had yet to be restored or rebuilt by 2016, reducing the capacity of the nation during the storm events. Puerto Rico, however, had not experienced such a dramatic event recently, and the built infrastructure present in the area was better equipped going into the storm. Most notably, Puerto Rico benefited most significantly from its status as a territory of the United States, and the significant vertical capacity that comes with that status. While foreign aid did flow into Haiti following Hurricane Matthew, the sums were a fraction of what was received by Puerto Rico to rebuild. While Haiti received nearly $13 billion in aid between 2011 and 2021,[62] the vast majority of that was from the 2010 earthquake response,[63] and aid requests since 2016 have fallen short of that which was requested, highlighting the challenges of dependence on horizontal external capacity to recover. Puerto Rico, which also faced substantial challenges following the 2017 storm, has seen over $30 billion in aid directed to the area, including $9.4 billion to strengthen the electric grid, $20 billion in urban development, and other billions in individual and miscellaneous aid.[64] When it comes to adaptive capacity (C_a), striking differences can also be seen in governance, where Haiti has seen a continued decline in coordination and representation. Following Hurricane Matthew, the nation gradually lost its representative government, with its last elected senators leaving office in 2023, and currently maintains an acting president, following the assassination of the formerly elected president.[65]

These two comparatives offer numerous points of analysis through this framework and highlight some of the potential capabilities. Prior to the 2016 and 2017 storms, which were relatively comparable, each location began with very different initial conditions, due to stark differences in governance and economics. Following the events, while both relied on external capacity, as defined under this framework, Haiti was heavily dependent on horizontal external capacity (coming from peer nations), while Puerto Rico benefited from vertical external capacity (coming from within its same governance structure). The impacts of the storms led to substantial instability in both locations, but the level of added capacity has helped Puerto Rico recover more effectively, despite the many challenges faced, while Haiti has slipped further into instability, with some labeling it a failed state. If the referent of analysis had been the United States itself, then at no time was the survival of the United States at risk from this storm. From the perspectives of both Haiti and Puerto Rico, they could both be seen as facing risks of survival unsupported, where Haiti has seen those risks increase following the event. Clearly, there are far more complexities than can be assessed in a brief overview, as presented here, but this example highlights the importance of capacity, external capacity, and vulnerability in amplifying or reducing the total risk to a referent from a similarly scaled disruptive event.

4.7.2 Territorial Invasion

As a second example of applicability, the invasion of Ukraine in 2022 represents a case for the influence of external coping capacity in armed conflict, and the importance of adaptive capacity internally.[66] Leading up to the invasion, analysts vocally assessed the potential for complete failure of the Ukrainian government, through a rapid invasion, and potential seizure of Kyiv. Analysts and commentators varied on both the assessments of whether Russia would initiate invasion (probability of occurrence), and in the event of an invasion, whether it would lead to the collapse of the Ukrainian government, which is more aligned with this framework. As an attacking force, Russia amassed a significant number of resources along the border leading up to the invasion, but doubts still persisted as to the likelihood of an invasion,[67] as well as the chances of success. The perceived capabilities of the invasion force, or approximations of combat power as outlined earlier in this paper, were significant enough that concerns were voiced by intelligence groups that Ukraine could fall within days of the invasion.[68,69] These prognostications of a rapid victory did not hold up over time, however. Despite significant uncertainty that accompanied the potential of invasion and the potential for success, it is reasonable to conclude that the survival of the nation was clearly at risk, and its intended collapse was a primary goal of the conflict,[70] although this intention was later rescinded. Based on the magnitude of the threat (M_t) and internal capacity (C_c and C_a), there was clearly legitimacy to the potential that an invasion by Russia threatened the survival of the government. Since that time, the situation has evolved substantially.

While the survival of Ukraine remains in question, the ratio of the event to the capacity has lessened from what would be an extreme risk of failure to a more moderate one. A key uncertainty remains as to the level of external capacity that will continue to be provided. While Ukraine entered the conflict with limited coping capacity, it could be argued that adaptive capacity was and continues to be significant, based on a willingness and persistence of Ukrainian defense that was unexpected by the invading force. The lack of coping capacity in terms of military capabilities was clearer and more significant, however, with Russia possessing significantly greater military capabilities prior to the invasion.[71] Since the beginning of the conflict, however, external coping capacity has helped to substantially bolster Ukrainian capabilities, as Western countries have provided significant military resources, intelligence, and leveraged sanctions against Russia over the invasion. While Ukraine has increased internal military capabilities, they are still heavily reliant on external capacity for necessary resources, and the ratio of the disruptive event to capacity has fluctuated depending on the level of support offered throughout the conflict, which could be represented in a time step approach. Without continued external capacity, Ukraine is likely to be unsuccessful in deterring further Russian advances and may again return to higher risks for survival going forward. As it is, Ukraine has already reached that point based on definitions offered by Lippmann and Wolfers,[6,7] where a sacrifice of interests and core values has been required in order to avoid complete collapse of governance.

While this example highlights the importance of external capacity, armed conflict can be particularly challenging to assign definitive outcomes to. Instead, the benefit here is to identify the potential for a legitimate threat to the survival of a referent to become clear. In this example, Russia's capabilities and the potential for action prior to the invasion indicated that should an event occur, the threat to Ukraine was legitimate, and many analysts have already identified it as such. It is worth noting that Ukraine had already begun to prepare for such measures, so this example is not a revelation, rather an alignment. However, narrowing in on a specific ratio of instability becomes much more challenging in cases of full-scale invasion, but rather the potential for highlighting a threat to survival is key. Further efforts from this example could bring attention to the need for the inclusion of a larger expert network as part of assessments, which would allow for a range of uncertainty to be assigned to disruptive event / capacity pairings. This could provide greater insights as well when assessing not only the potential for the threat to endanger survival, but also provide pathways for assessing future shifts in capacity or vulnerability.

4.7.3 Extending Examples

Each of the previous examples provide insights as to the application of this conceptual model, and how altering and exploring variables provide the ability to assess points where the survival or stability of a referent may be at risk due to a disruptive or destabilizing event. Modifications to each of these scenarios would also provide awareness about events that may pose significantly less risk, such as a Category 1 hurricane with partial exposure, or an isolated skirmish along national borders. Either of those events may pose security concerns but are unlikely to result in any of the referents involved in this analysis being faced with questions of survival For that to be a risk, the level of analysis would likely have to be more focused. Analysts seeking to expand on these efforts also can provide greater depth to any of the components of the associated risk function and model to refine the focus. Both examples, however, are rooted in real-world events that provide insights in modifying the analysis. Other applications involve the ability to formulate new and potential events, to perform pre-emptive threat and hazard assessment from a planning perspective.

4.8 Discussion

The potential applications for this framework offer multiple perspectives for analysis in the areas of disaster studies and international security, and the generalized nature is intended to provide flexibility for many potential referent objects. One of the most straightforward uses is the ability to identify potential points of "legitimate" or objectively justified securitization. This is not to say legitimate in the normative sense, but rather to help answer questions of whether a particular event (threat or hazard) may pose a danger to the stability (or survival) of the referent in question. This allows a more objective, although not absolute, analysis akin to determining whether an act of securitization may be seen as "just" within the Just Securitization Theory (JST). This also does not assist in identifying whether a securitization is likely to be successful (Criterion 5 of the JST), but it is more probable that a legitimate risk would lead to securitization if the probability of occurrence was seen as high.

Another potential use of this model is the ability to compare changes to the status of a system over time, as changes in capacity, or the magnitude or exposure of events change over time. This temporal dimension allows both backward and forward analysis, to understand where tipping points may occur, or how they may have occurred differently given a slight change in variables. This latter component makes it compatible with approaches used in similar fields, from scenario planning to downward counterfactuals in disaster studies. Spatially, this also allows for a comparison of multiple referents when faced with similarly framed disruptive events, based on unique capacities. This provides the ability to perform comparative analysis of a similar event if it were to affect different referent objects. Applying both temporal and spatial dimensions, it also supports the ability to analyze states experiencing compound or cascading events through time.

Based on connections to PRA approaches, this model also has the potential to support a greater quantification of risk to referents or units of analysis based on specific disruptive events in the future, at multiple levels of analysis. However, the model still retains the ability to use a more qualitative perspective, supporting creative thinking approaches and the ability to "workshop" problems. Within the qualitative approach, scenario-based planning efforts can be aligned with potential pathways of disruptions for units, or further quantified to strengthen analysis. Other potential applications include the analysis of capacity across referent objects (horizontally and vertically) to identify events that may lead to a reduction of support via external capacity, increasing the likelihood of a referent object collapsing. If desired, this could even support the ability to scale down to the smallest levels of analysis, identifying areas where individuals, groups of individuals, or local communities may be most prone to instability that could be supplemented to prevent destabilization, an area where the field of international security studies has previously faced challenges. The authors of this paper hope that with broader adoption, similar applications have the potential to test, expand, and improve the approach, to provide planners, analysts, and policymakers greater utility when identifying significant disruptive events for their specific fields and perspectives.

As with any conceptual model, this model is constrained by its intentions. While this model explores the potential impacts of a disruptive event on a referent, it does not assess the probability of that event occurring and therefore does not produce a probability of total risk, but rather a likelihood that a particular event would cause failure of the referent. This is a notable caveat, as in total risk analysis, the probability of an event is a key component of risk prioritization. While approaches may be supplemented in the future to support that approach, the intention here is more closely aligned with a logic of "If this event were to happen, Then how likely is the referent to survive," as opposed to traditional approaches in disaster studies to prioritize risks based on a combination of likelihood and magnitude. This has great utility both in exploring past events, but particularly in exploring the potential unrealized, and complex, events that may be expected under radically different climate conditions in the future. However, it also poses utility in a wide range of traditional risk assessment approaches.

4.9 Conclusion

This article outlines a new conceptual approach toward merging the study of risk related to threats and hazards to nation states and other units of analysis, through their unification under the study of disruptive events. Based on the magnitude of an event, the exposure to risk, the vulnerabilities associated, and the capacity of units to cope with and adapt to disruptive events, this framework provides a comprehensive, scalable, and extensible framework capable of exploring a wide range of uncertain risk. The framework extends the fields of disaster studies and international security studies, providing a common and interoperable approach toward assessing domestic and international risk of instability. Additionally, this framework provides a common way to conceptualize a wide range of risks, from the individual to the international level of analysis, across sectors, based on a simplified view of stability in the face of potential tipping points.

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Chapter 5: General Conclusions

5.1 Summary of Work

The core chapters of this dissertation offer three perspectives on issues of climate change as they relate to risk and security. Chapter 2 offers a perspective on local hazard based analysis, and implications for decision-making under uncertainty. Chapter 3 explores the potential that well-intended measures to combat or delay the worst impacts of climate change may lead to unintended consequences at local, national, or international levels, and highlights the current challenges in managing those risks. Chapter 4 provides a look at existing approaches toward assessing risk, and proposes a new all-scales, all-sector approach toward identifying catastrophic risks that may endanger the survival or assets, communities, or other referents of analysis. Combined, these chapters explore the intersection of multi-scalar risks and securitization as they pertain to climate change, and provide lessons and insights from each perspective.

5.2 Lessons Learned

As of this writing, proactive global abatement of greenhouse gases appears unlikely to be successful at avoiding critical thresholds of climate change,[1] without significant and rapid shifts in global policy. As a result, the need for adaptation-based approaches toward climate change are likely to grow, as individuals, local communities, nation-states, and regional institutions attempt to manage the growing risks. Through the exploration of local hazard assessment processes and the analysis of security and ethical concerns at regional and global levels, this dissertation highlights several complex challenges faced in adaptation-based approaches to issues of climate security. The final chapter of this dissertation will provide a summary of findings and outcomes, a discussion on future pathways in climate security discourse, and concluding thoughts on the challenges faced as climate security at all-scales becomes a more prominent issue of concern.

5.2.1 Local Hazard Assessment

The assessment of local hazards is a critical step toward local adaptation against climate risks and the development of hazard mitigation plans. Communities have long faced challenges in identifying and minimizing the impacts of natural disasters and attempts to do so go back to early human civilization. One of the challenges in doing so is understanding the scale of events that is likely to affect a particular area, especially as drivers change from historical norms. In

Chapter 2 of this dissertation, a look at the challenges of modeling a single climate hazard was explored for sections of Interior Alaska, in the United States. Modeling of these river systems provides a mechanism to inform local area planners as to the potential shifts in flooding that could be expected, so that measures to prepare for those floods can be taken proactively. In providing these insights, the research from Chapter 2 acts as a valuable tool that can help to avoid or reduce costly and dangerous extremes but faces significant limitations.

Future extreme events depend greatly on the scenarios that become the predominant future. Many modeling efforts focus on the most extreme future, currently Representative Concentration Pathway 8.5 presented by the IPCC in Assessment Report 6, as this effort chose to do. This can be helpful, in that it may offer a glimpse of the most extreme outcomes, to plan for the worst. However, this future is also the greatest deviation from the present, leading to substantial uncertainties in realized impacts. Additionally, if every community were to seek planning based on the worst possible outcomes, it may lead to the overtaxing of resources, diminishing the capacity or capabilities available to provide flexible adaptation, particularly if that future does not play out as predicted. The IPCC specifically does not attach probabilities to their scenarios, but rather they are highlighted as potential pathways based on human behavioral choices and energy pathways. Communities therefore are forced to make choices based on perceived risks in future projections. The work in Chapter 2 of this dissertation outlines potential shifts in streamflow, seasonality, extreme events, and other changes to local rivers. While this provides insights, it cannot be taken as a high confidence forecast, due to the high number of variables influencing future outcomes. Therefore, communities will in many cases have to prioritize a balance of future extremes with current needs, as they have often had to do. What this provides is a longer view of potential unidentified risks that decision-makers must weigh against capabilities, based on perceived needs.

5.2.2 Local to Global Security and Ethical Impacts

The emergence of geoengineering as one potential mechanism to reduce climate impacts, both regionally and globally, presents new concerns at all levels of analysis, for ethical and security considerations. This dissertation highlights the complexity of adaptation mechanisms intended to limit or prevent some of the worst outcomes of climate change through methods that include removing carbon, reducing surface-warming, increasing albedo, or maintaining the thermal mass of cold regions. It is important to note that weather or climate modification itself is not an inherently new idea, but early efforts to actively modify weather were restricted by international treaty due to the concerns of generating unintended consequences and their potential for conflict. While many researchers often identified these exploratory efforts as an experimental and largely benevolent approach toward reducing hazard impacts,[2] it became apparent from a political perspective that there was incredible potential for harm, and the Environmental Modification Treaty (ENMOD) was put in place to prevent malicious or reckless application of projects that may have significant effects against other nation-states.[3]

However, concerns over climate change are renewing interest in these technologies, with a perceived urgency. This urgency acts as a stepping stone to securitization efforts, through a justification of extreme measures, with many proponents arguing that the cost of doing nothing is worse than interventions. Such measures have generated substantial concerns, however, due to the potential risks associated with large-scale deployments. As the exploration of multiple technologies may present complex or compounding considerations, the risk is not solely about the cost of doing nothing, but rather the cost or risks of each comparative technology against other proposed solutions as well.

While initially the research in this dissertation explored ethical and security concerns surrounding potential geoengineering efforts in the Arctic, following the release of the paper in Chapter 3 additional efforts have continued to progress in the field, including real-world testing. Crowdsourcing of geoengineering efforts have expanded,[4] while studies have further highlighted the potential disproportionate results of geoengineering efforts at different latitudes, even when undertaken regionally.[5] In response to rogue actors in this realm, some governments have already begun to further restrict uncontrolled experiments.[6] It is clear that geoengineering is moving beyond thought experiments and the theoretical, and into the realm of not only feasible, but plausible, as unilateral actors begin to see justification to engage in these measures without diplomatic agreements or oversight. This holds the potential for significant risks from both ethical and security perspectives, as outlined in Chapter 3. As efforts increase to maintain or limit warming globally, the potential for negative effects in local or regional areas are important to consider. Additionally, as shown in modeling experiments, the methods or location of deployment are likely to produce varying results globally, leading to national or regional outcomes that may not only be negative, but could be seen as threatening the stability of those nation-states. Therefore, Chapter 3 acts as an important reminder to the need for holistic consideration of any proposed measures, as the potential exists for negative social consequences to outweigh perceived benefits to the physical environment. Any large-scale interventions should be guided by not only precautionary principles but also a balance of risks to those affected by any interventions with the perceived benefits.

5.2.3 Tipping Points and Points of No Return

The exploration of risk as unrealized impacts is an important part of climate change planning. While numerous approaches have been taken in the past to explore risks to infrastructure, communities, and assets, few approaches focus on catastrophic risks that endanger the very survival of people, systems, or institutions. Chapter 4 addresses a critical need in security studies, by incorporating a more comprehensive approach from disaster studies into the understanding of justification of extreme measures, from a multi-scale, multi-dimensional perspective toward risk and security. In general, success and recovery of a system is far more common, so many efforts are focused on understanding how to achieve those measures over time.

By looking at potential failure points, it not only addresses the risks seen as most dangerous to a referent of analysis, but also helps to explain when securitizing actors may be acting from a perspective of "legitimate" threats or hazards, that may be identified as points of securitization. It also provides analysis for an understanding of where cascading or complex risk may present itself over time, and an identification of where external capacity may be limited, either due to the severity of the disruptive event, as outlined in the framework, or because the availability of external capacity may be limited due to overcommitment or reluctance toward commitment by peer or internal entities.

In addressing a multi-scale and multi-sector approach toward the assessment of catastrophic risk, in alignment with existing securitization theory, this also provides a common language and perspective in understanding and communicating risk between international security scholars and disaster scholars, which is particularly important due to the growing interdependence of the two fields. While it is rare and difficult to identify the specific failure point of any nation or governance structure in advance, this framework provides an ability to understand when a particular referent faces events that are likely to lead to destabilization. Because each event presents different challenges to a referent, general markers or quantifications of instability are insufficient to deal with the range of risks they may face. Instead, it is important to address the ways different risks present, to understand where particular systemic weaknesses, or shortcomings in coping and adaptive capacity, may exist, to allow for those to be addressed more proactively. Combined, this framework provides a clear conceptual approach, both in terminology and in application, to highlight the importance of these catastrophic risks in complex environments, where both direct threats as well as conditions that may increase harm are likely to occur simultaneously. Long-term, this also provides the foundations for a stronger approach toward modeling and scenario planning, through the support for quantification of geospatial and political (as well as security) risk under a common framing.

5.2.4 Unifying Themes

The role of climate security in discourse and planning is increasing as the impacts of climate change become more prevalent. The three papers presented in this dissertation highlight different aspects of what is a more holistic challenge, and they explore the intersection of scales, governance, and risks when it comes to climate security. Contributing to the complexity of decision-making efforts surrounding climate change is that it presents different challenges to different levels of society and geographical locations, despite alignment under a common causal umbrella. Addressing these challenges requires an approach that is both holistic in perspective, but also one that is scalable, flexible, and uniquely adaptable. Due to its presence at all scales, it has the potential to produce unintended feedback, as different actions undertaken to mitigate or adapt to its impacts sometimes work in contradictory or detrimental ways, producing risks that may be seen as unacceptable to those affected. While each chapter in this dissertation focuses on a different perspective as it relates to climate security, each also presents linkages to other scales or geographic concerns. A lack of global consensus, combined with global causality, shifts responsibility to local or regional decision-making bodies to prepare for current and potential future conditions. Simultaneously, these localized efforts produce the very real potential for global impacts, through both changes to physical systems, but also social systems and stability. Even though these results are limited in nature, and assess a limited scope, they provide insights to broader lessons in governance and structural challenges.

From a local sense, flood mitigation is not a new problem. Human societies have explored ways to reduce flooding and manage waterways for beneficial purposes for thousands of years, to varied results.[7,8] In some cases, attempts to do so failed specifically due to long-term local shifts in climate.[9] The ability to model these changes, however, is a relatively recent advance in human capabilities, which provides a forward-facing look at local impacts to extreme events, should the system experience the substantial changes that are possible under future climate projections. This newly developed capability provides modern decision-makers a unique opportunity to use those insights to prepare communities, potentially well in advance of the actual impacts being realized. However, this also presents significant challenges for the proactive decision-maker. While models offer representations of future change, they do not do so with certainty. Therefore, any insights gained must be balanced with the resources available to the community, and the understanding that those futures may not be perfectly realized, potentially due to model uncertainties that falsely predict, or human uncertainties that shift the underlying conditions unexpectedly.

Both flood analysis (Chapter 2) and Arctic geoengineering (Chapter 3) present challenges to governance when it comes to future conditions under climate change. Computational models offer a glimpse of greater understanding of physical processes under a shifting climate, but continue to be constrained by human decision pathways, limited available observational data, and computational resource availability, as local communities and governments attempt to plan for an uncertain future. Decision-makers attempting to mitigate the potential challenges face significant uncertainty, both to the models identifying these risks, but also based on the tolerance, acceptance, and willingness of their constituents or partners. Efforts undertaken to deploy mechanisms to reduce global temperature rise may face similar uncertainty when it comes to methods, scalability, and impacts, both for social and natural systems. A rise in the perceived urgency for action to mitigate climate is driving an increase of geoengineering related measures and other forms of adaptation, but each option presents its own risks and challenges, requiring a holistic look at the impacts, regions affected, and potential cascading effects of major measures. It is unlikely that there will be perfect solutions to climate governance and decision-making, either in mitigation or adaptation, but ignoring the unintended outcomes produced by mitigation and adaptation projects on other populations is likely to exacerbate problems, and therefore significant concern exists that fast-moving efforts intended to limit the worst risks of climate change will produce unintended consequences themselves.

5.2.5 Policy Implications

In addition to the thematic and theoretical applications of this dissertation, the component work of the core chapters also offers opportunities for informing policy and decision-making at various scales. Chapter 2, through identifying potential future hazards, offers an example of improved forward-looking planning, which can inform proactive policy toward local hazard mitigation and adaptation. This long lead time allows for important community planning efforts, from the deployment of infrastructure to the effective management of zoning and development planning, each of which can benefit from detailed modeling and study of adverse or unexpected impacts, allowing for precautionary adjustment. While individual communities often have more flexible planning structures, the decadal or multi-decadal planning window required for unforeseen extreme events, combined with the difficulty of risk perception for previously inexperienced events benefits greatly from advanced perspectives.

When looking more broadly, Chapter 3 offers insights to policy and planning at a regional and global scale, as it pertains to the potential for security escalation highlighted through geoengineering efforts. Similar international concerns in the 1970s, following advances in scientific research on weather modification and specific military operations in the late 1960s and early 1970s,[10] led to the creation of the ENMOD treaty, as nations became increasingly concerned with the intentional use of weather modification for warfare.[3] With the scale and the potential for extreme measures involved in proposed geoengineering solutions, the potential for unintended consequences necessitates proactive policy considerations to prevent escalations between Arctic nations, given the history associated with weather and climate modification. Since many proposed initiatives are intended as domestic or peaceful measures, ENMOD and similar treaties may be limited in application. Even the Convention on Biological Diversity,[11] and its specific additions regarding geoengineering in 2010,[12] offer primarily an advisory stance that scientific diligence should be performed prior to deployment. Therefore, extensions to international treaties or regulations may be required to limit large scale impacts, the actions of rogue actors, or the perceived existential threats that may accompany uncontrolled deployments or projects lacking international oversight. Chapter 3 offers both areas for proactive policy potential, as well as pathways that may highlight feasible mechanisms for achieving consensus-based opportunities for managing this growing challenge. While current international conflicts may make consensus-based work in the Arctic difficult, the challenges of climate change and proposed geoengineering work are likely to require multidecadal policy agreements to limit negative outcomes.

Finally, the tipping points model, in Chapter 4, offers a planning tool for all-scales of governance and analysis. At the local scale, this approach offers a mechanism for application-based assessment of hazards and threats, to identify capacity building needs. Scaling up, at the national level, the tipping points model offers insights for capacity building, and an understanding where international or peer nations may benefit from added capacity, either temporary or permanent, and where there is potential for shared resource allocation to buffer the worst impacts of climate change and international conflict. At the global level, the model in Chapter 4 offers policy planning insights for identifying international capacity shortages, and where the potential for multiple concurrent disasters may limit spare capacity. The model provides both analysts both academic and operational utility, as a way to scope and plan in a consistent manner, and to pre-identify potential failure points through various mechanisms, offering both qualitative and quantitative methods to co-assess numerous threats and hazards. This also holds the potential to assess claims more effectively for extreme measures that may be out of scope or exaggerated beyond the scale of the existential risk being faced. With additional advances to this model, it may also serve as a broader threat-hazard assessment tool, to improve prioritization of risk management approaches in policy and planning.

5.3 Discussion and Future Work

As with any work, this dissertation is not without its limitations. Each chapter presented unique challenges, and the work is constrained by those considerations, but offers future opportunities. Chapter 2, which employed a computational modeling focus, presented numerous challenges. The limits of computational resources and availability required scaling down of potential scenarios, and reduced the number of pathways that could be explored. While this may help identify "worst case" outcomes in high flow or extreme cases, it reduces the ability to translate results to decision-makers, as it lacks a broader understanding of incremental changes to the system. Future work in this area would benefit from greater computational resources, both to widen the understanding of system changes, but also to speed the work. The limited computational resources, and large datasets, required regular data stewardship and reduction of one data set to produce the next. This process requires significant overhead to do so, slowing progress substantially. Added resources could speed the returns and provide more robust simulation outcomes. Building on that, and advancing decision-maker approaches, this work would benefit from greater inclusion of local stakeholders, to identify and assimilate outcomes of similar efforts.

Geoengineering is an area that continues to rapidly grow. The work in Chapter 3 identified a number of areas for future expansion, and some of these have already begun to produce collaborative opportunities through working groups and workshops. There is a growing demand for radical approaches to address climate change, and this demand generates the potential for substantial risk, with both intended and unintended consequences. The work here provides a basis for exploration, but would continue to benefit from broader discussions, from local and regional engagement, participation and development of oversight and planning groups, and the building of collaborative networks to explore the potential outcomes of these events through scenario planning and computational modeling. While weather modification efforts have existed for several decades,[2,13] the scale of geoengineering and the potential impacts require more comprehensive approaches than may have existed in the past, and hold potential for global level consequences. This work also aligns well with the need for comprehensive approaches to security and risk identification.

As a major outcome of this dissertation, the security tipping points model forms the basis of a new approach toward identifying catastrophic events in a unified environment and highlights the potential for just securitization events within existing frameworks. However, it also establishes an opportunity for greater quantification of security related events, and could be a stepping stone toward improved modeling efforts to assess stability potential. Combined, the efforts made, and progress gained through this dissertation provide an opening for new directions in merging computational modeling with security concepts, which have traditionally existed in more qualitative realms, to better address the complexity of socio-cultural decision-making that depends on feedback from natural systems modeling. In a future of climate challenges, the ability to identify conflict and catastrophe points with added programmatic intelligence also provides opportunities to advance lead times and buffers, to reduce destabilization. This dissertation supports that vital need, and opportunities for bridging dialogues between risk management and security offer valuable pathways for future research.

5.4 Final Conclusions

Even under conservative projections, climate change is expected to produce significant impacts in parts of the world that are already near irreversible thresholds, or tipping points, that are likely to result in fundamental shifts in risk potential. Issues of scale will continue to challenge those responsible for managing these risks without common tools and frameworks. It is critical that analysts, policymakers, and field experts are able to identify the potential for complex interactions between climate and human behavior, and how those interactions play out at different levels of analysis, and in different spatial and temporal dimensions. Particularly important is the understanding of points of instability, conflict, and systemic failure, as those points bring the greatest impacts to humans and ecosystems, and require significantly more resources to recover from, as opposed to maintaining a system.

This dissertation highlights the need for advances in the understanding of climate security through interconnected approaches toward risk assessment. As local communities attempt to manage the expected shifts in climate, they may also be faced with challenges presented by efforts to diminish those changes, requiring adaptive and flexible planning approaches to become more widespread. The exploration of two perspectives on risk, from local to global, emphasizes the need for a multi-level understanding, as well as the examination of catastrophic risk. This outcome led to the introduction of a new conceptual framework designed to analyze systemic failure points across levels of analysis, and through temporal dimensions. This approach addresses a notable gap in climate change research, and provides a mechanism to improve the analysis of climate related risks through an all-scales approach toward security discourse that includes both disasters and conflict as overlapping drivers of risk, and can be applied both within climate contexts and beyond. It also establishes a foundation for future research to advance these efforts through the application and refinement of the approaches outlined.

The work enclosed in this dissertation addresses climate security as an issue that, unlike many challenges humanity faces, requires an all-of-society approach to be successful. Because of the impacts that are likely to be experienced at different levels of governance, issues of climate security require multi-disciplinary approaches, which may otherwise be reduced in effectiveness without a common dialogue. By exploring multi-faceted, multi-scale concerns, from local adaptation to global geopolitical considerations, this dissertation improves the ability of researchers, practitioners, and decision-makers to find that common ground and language to discuss and explore these issues effectively, in an effort to prevent the most catastrophic impacts from being realized. To avoid the worst impacts of climate change, our collective future depends on our ability to holistically understand these problems.

5.5 References

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