Defense Science Board
DSB
Department of Defense

2023 Defense Science Board Summer Study on

CLIMATE CHANGE AND GLOBAL SECURITY

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This report is a product of the Defense Science Board (DSB).

The DSB is a Federal Advisory Committee established to provide independent advice to the Secretary of Defense. Statements, opinions, conclusions, and recommendations in this report do not necessarily represent the official position of the Department of Defense (DoD).

This report summarizes the findings and recommendations published by the Defense Science Board for the 2023 Summer Study. The purpose of this study is to recommend a strategy for anticipating the global stresses and possible conflict due to climate change and provide investment priorities for new systems and technology.

Climate Change and Global Security

Climate change has emerged as one of the most pressing challenges of our time and imposes severe implications on global security.

Climate change has emerged as one of the most pressing challenges of our time and imposes severe implications on global security. Climate change acts as a "threat multiplier," amplifying existing vulnerabilities, enhancing regional instability, and generally fostering conditions conducive to conflict. Many of these stresses will affect how the DoD should strengthen deterrence and prepare for potential future conflict. The global impacts of climate change, and the failure of current diplomatic approaches to mitigate its effects, mean that time is of the essence for the DoD to prepare to operate in a climate-changed environment.

The findings and recommendations of this report consider the following:

- Several regions of the world present significant challenges due to the impacts of climate change, such as greater accessibility in the Arctic and uninhabitability in parts of Africa and will require the DoD to prepare for conflict in new ways.
- Climate change will likely open avenues for new dimensions of conflict, including mass migrations and weaponization of critical resources. The U.S. can have a positive influence on regions affected by severe weather events by enhancing its humanitarian assistance and disaster relief (HADR) capabilities and improving outreach through U.S. and international agencies amid greater climate diplomacy.
- Climate change will affect DoD force readiness and infrastructure. The DoD will need to improve aspects of its defense systems to support operations in extreme environments and must reexamine the location and protection of its military bases.
- To ensure proper decision-making support in the face of climate change, the DoD must leverage and institutionalize emerging efforts to understand and anticipate its impacts by enhancing state-of-the-art climate situational awareness and modeling data sets, techniques, and applications.

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DEFENSE
SCIENCE BOARD

MEMORANDUM FOR UNDER SECRETARY OF DEFENSE FOR RESEARCH AND ENGINEERING

SUBJECT: Final Report of the Defense Science Board Summer Study on Climate Change and Global Security

I am pleased to forward the final report of the 2023 Defense Science Board (DSB) Summer Study on Climate Change and Global Security. This study examined important considerations for ensuring that the Department of Defense (DoD) prepares for the impact of a changing climate.

The report provides a high-level overview of how a changing climate may directly or indirectly affect regions in the world, presenting new challenges for improving global security and addressing potential conflict. The DSB focused its assessment, findings, and recommendations in several areas, including:

- Improving climate situational awareness and decision support
- Enhancing force readiness in extreme environments
- Preparing for potential military base and facility vulnerabilities
- Strengthening humanitarian assistance and disaster relief capabilities
- Anticipating resource scarcity and supply chain vulnerability

The impact of a changing climate requires the DoD to continually review the stresses and stability in regions across the world and to anticipate the capabilities and adaptations needed. The DSB recognizes the significant climate-related efforts underway across the DoD and through other agencies and organizations and identifies options for further progress. The DoD has many opportunities to work closely with our Allies and partners to build a comprehensive and coordinated approach to prepare for a changing climate worldwide.

I fully endorse all the recommendations contained in this report and urge their careful consideration and adoption.

Dr. Eric D. Evans
Chair, Defense Science Board

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Executive Summary

Climate change is one of the most pressing challenges of our time. No longer a distant or abstract threat, the ramifications associated with a rapidly changing climate present an escalating danger with national and global security implications. The increasing trajectory of global greenhouse gas emissions and other catalysts, such as an increase in deforestation and urbanization, have combined to increase ambient global temperatures. The DoD, with support from Congress, has begun a number of efforts to address the effects of climate change. As environmental impacts mount, the DoD will need to do more to maintain readiness across the U.S. military enterprise.

Climate change can amplify existing vulnerabilities, enhance regional political instability, open new modalities of conflict, and potentially foster conditions conducive to conflict. As a result, climate change is reshaping the geopolitical terrain, with regions previously peripheral to conflict becoming potential hotspots.

Second-order effects of climate change have created difficulties in nations with low adaptive capacity. Such nations are often the least able to contend with radical temperature variations, severe flooding, and long-lasting drought. While the exact nature and severity of these challenges can evolve, regions at risk for potential conflict may differ from current and past areas of concern. The Arctic will become more accessible, parts of northern Africa and the Sahel may become increasingly uninhabitable, regions of the Middle East may experience higher levels of food and water scarcity, and the low-lying areas of South Asia may be increasingly susceptible to coastal flooding. The full spectrum of military operations must be prepared to adapt to these harsher environments. The challenges in these regions and others will require the DoD to prepare for operations in new ways, using new tools.

Climate change may result in new dimensions of conflict and opportunities for influence. Resource scarcity and contested access to essential resources (e.g., food, water, energy) could contribute to more frequent and complex regional instability, conflict, and possibly mass migration, particularly in regions with low adaptive capacity. Supply chains, including for minerals and rare earths crucial to defense technologies, are often found in areas controlled or influenced by adversaries. These supply lines are further strained by climate pressures, necessitating innovative approaches and increased monitoring. The DoD must adapt to counter these non-traditional threats and leverage opportunities for influence in affected regions.

Worldwide trends suggest an increase in severe storms, droughts, flooding, and fires. The military's expertise in providing Humanitarian Assistance and Disaster Relief (HADR) creates an opportunity for the U.S. to influence affected regions positively during times of strife. New HADR capabilities may involve new sensing systems and communication technology, the rapid adaptation of commercial technology in the initial stages of the relief effort, and faster logistics. Climate diplomacy and influence will become a new battleground for great power competition. Improving HADR understanding and liaisons with other U.S. and international entities may be a significant part of future alliance building.

Moreover, climate change will affect DoD force readiness and infrastructure. Greater temperature variations in expanded operating locations worldwide suggest that the DoD must improve infrastructure resilience and adapt service member performance. Service members may have to operate in a wide range of environmental conditions: from extreme heat to extreme cold, from underwater missions to high-altitude flights. The Department will need to reexamine the location and protection of its military bases as climate change drives the need for a forward presence in new regions. Additionally, replacement facilities may be needed if mitigation measures cannot keep threatened bases operational.

To ensure proper decision-making in the face of climate change, the Department must improve its climate situational awareness and leverage and institutionalize emerging efforts across Combatant Commands (CCMDs). Presently, no single entity in the DoD orchestrates the baseline activity to understand and anticipate the impacts of climate change at the regional scale. To be effective in this future environment, DoD must create a climate planning cell and engage the U.S. interagency in climate situational awareness, modeling, and decision-support. This collaboration would allow the DoD to anticipate future instability and plan for an earlier response.

Climate change is likely to transform the global security landscape. The Department of Defense must adapt its strategies, operations, and infrastructure to meet these challenges head-on. By embracing innovation, enhancing collaborations, and redefining its approach to conflict and humanitarian assistance, the DoD can safeguard national security and emerge as a pivotal player in the global response to climate change.

Introduction

U.S. Secretary of Defense Lloyd J. Austin III has highlighted climate change as a national security threat and the importance of addressing its challenges within the Department of Defense (DoD). During his confirmation hearings and subsequent statements, Secretary Austin warned that the impacts of climate change, such as the increasing frequency of extreme weather events, rising sea levels, droughts, floods, and others, exacerbate existing security challenges and contribute to instability in various regions of the world. He pledged to incorporate climate considerations into the DoD's strategic planning and decision-making processes, including assessing the impact of climate change on military operations, infrastructure, and readiness. As a result, the DoD has worked to elevate climate change into national security planning and is integrating climate considerations into policies, strategies, and partner engagements within the Office of the Secretary of Defense (OSD), in acquisition and sustainment processes, and within the Services, the Combatant Commands, and other elements of the Department. A lot of excellent progress has been made. Figure 1 shows some of the key DoD products related to climate change, such as the DoD Climate Change Adaptation Plan and the DoD Climate Risk Analysis. These documents serve as high-level sources containing core information on how the Department plans to adapt to and address climate change.

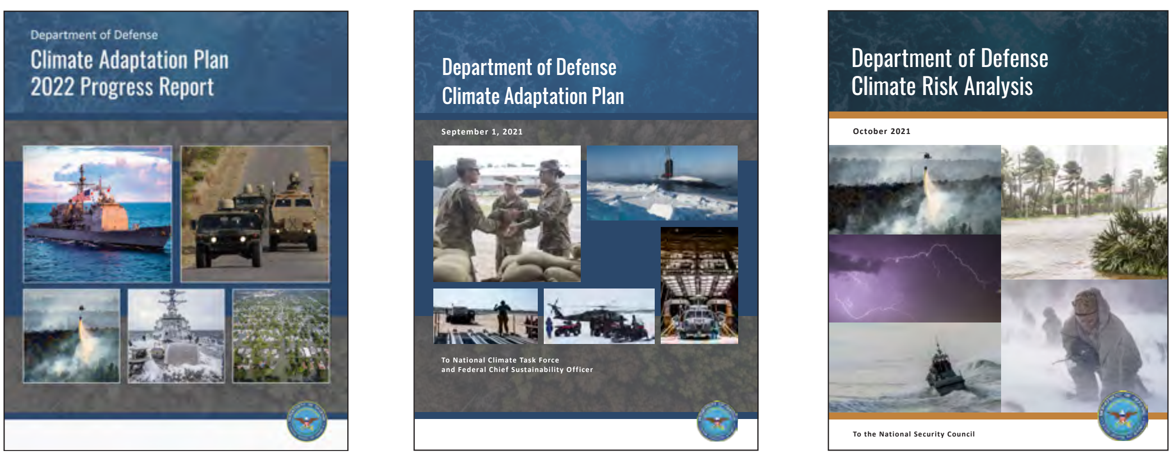

Figure 1. Climate action reports released by the DoD.[1]

The objectives of this DSB study are to:

- **Recommend a strategy for anticipating global stresses and conflict:** As the climate evolves, the study's first objective is to craft a strategy that enables the DoD to anticipate and proactively address the global stresses and potential conflicts it engenders.

1. Figure 1 Source: Department of Defense, https://www.defense.gov/spotlights/tackling-the-climate-crisis/.

- **Provide investment priorities:** To effectively tackle climate-driven security threats, the study delineates investment priorities across near-term, mid-term, and far-term horizons to ensure that our future defense systems and technologies are aligned with the realities of climate change.

The study's Terms of Reference requested that the DSB:

1. Investigate the influence of climate change on global political and military stability, highlighting regions where current and future security stresses may escalate the risk of regional conflicts.

2. Investigate new dimensions of conflict driven by climate change.

3. Assess and recommend investments in new defense capabilities that anticipate the evolving needs posed by climate change.

4. Identify areas where Allies and partners can collaborate to address the global security impact of climate change.

Over the course of the study, the DSB heard from dozens of experts from academia, the DoD, the private sector, Federally Funded Research and Development Centers (FFRDCs), and other federal agencies to inform this report. In summary, climate change is real, and the DoD must take further action to prepare for it better — now.

Widely variable weather patterns, more severe storms, rising sea levels, and fluvial, pluvial, and coastal flooding warrant early responses to combat climate change effects. Negative implications to service member training, bases, supporting infrastructure, and DoD and civilian facilities sustaining service member's families, schools, housing, and transportation demand action across the DoD.

The strife often associated with climate change contributes to increased great power competition and regional tensions worldwide. While the DoD has made much progress in recent years, the current approach to incorporating climate change considerations into operational planning should be further improved. Improved decision support tools and Department and Interagency-wide coordination are reasonable first steps. Moreover, the DoD can further leverage Allies and partners to increase planning and resilience to climate change impacts.

Before delving into this study's detailed findings and recommendations, it is worth briefly considering the current state of climate change science, what we know, and what we have yet to learn.

Climate Change Science: Implications and Gaps

Climate Change Science: What We Know

To ground our study in scientific understanding, it is imperative to acknowledge the following fundamental facts:

- On average, the planet has warmed by at least 1.1°C since the start of the industrial era, with widely discernible global consequences. Figure 2 shows the earth's average temperature in the month of September from the pre-industrial era through today. As seen from the figure, 2023 was the hottest year on record. As the Economist noted on January 12, 2024, "the past nine years, one

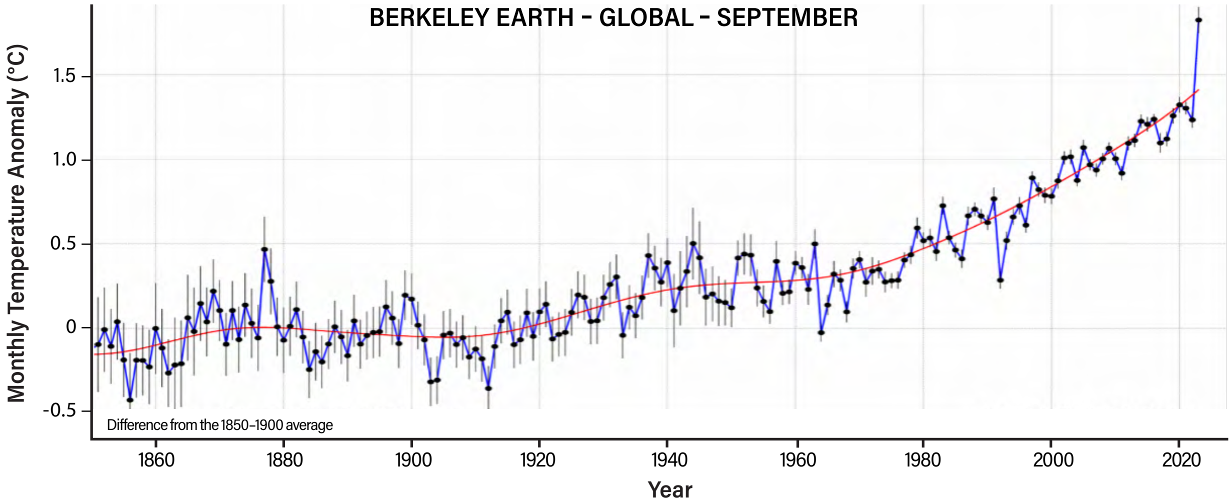

Figure 2. Global temperature upward trend.[4]

after the other, have been the hottest ever recorded."[2] But even against this background, 2023 was remarkable, for it was the first time in recorded history that every day of 2023 was 1° Fahrenheit above pre-industrial ambient temperatures when averaged across the globe.[3]

Climate change manifests globally in the form of increased severity and frequency of extreme temperatures and disruptive extreme weather events.[5]

- If current trajectories persist, projections indicate that the planet is highly likely to warm by **an additional** 2° to 3.5°C (a total of 3 to 4.5°C above pre-industrial levels) by the end of the century.[6] Figure 3 shows the projections of the United Nations' Intergovernmental Panel on Climate Change's (IPCC) 6th Assessment Report published in 2023 and represents the best scientific consensus from thousands of today's climate scientists.
- Despite the growing realization that curtailing actions must occur, the Board considers that viable scenarios for significant alterations to this trajectory in the near term (one to two decades) remain elusive.
- The earth is a complex system, and the impact and consequences of climate change are multifaceted, entwining climatic, human, and social factors into a complex web.

2. "Eight charts illustrate 2023's extreme weather," The Economist, Jan. 12, 2024, https://www.economist.com/graphic-detail/2024/01/12/eight-charts-illustrate-2023s-extreme-weather.

3. "Copernicus: 2023 is the hottest year on record, with global temperatures close to the 1.5°C limits," Copernicus, Jan. 9, 2024, https://climate.copernicus.eu/copernicus-2023-hottest-year-record.

4. Figure 2 Source: Berkeley Earth, https://berkeleyearth.org/data/.

5. IPCC, Climate Change 2023: Synthesis Report, Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Geneva, Switzerland: IPCC, 2023), https://doi.org/10.59327/IPCC/AR6-9789291691647.

6. IPCC, Climate Change 2023: Synthesis Report.

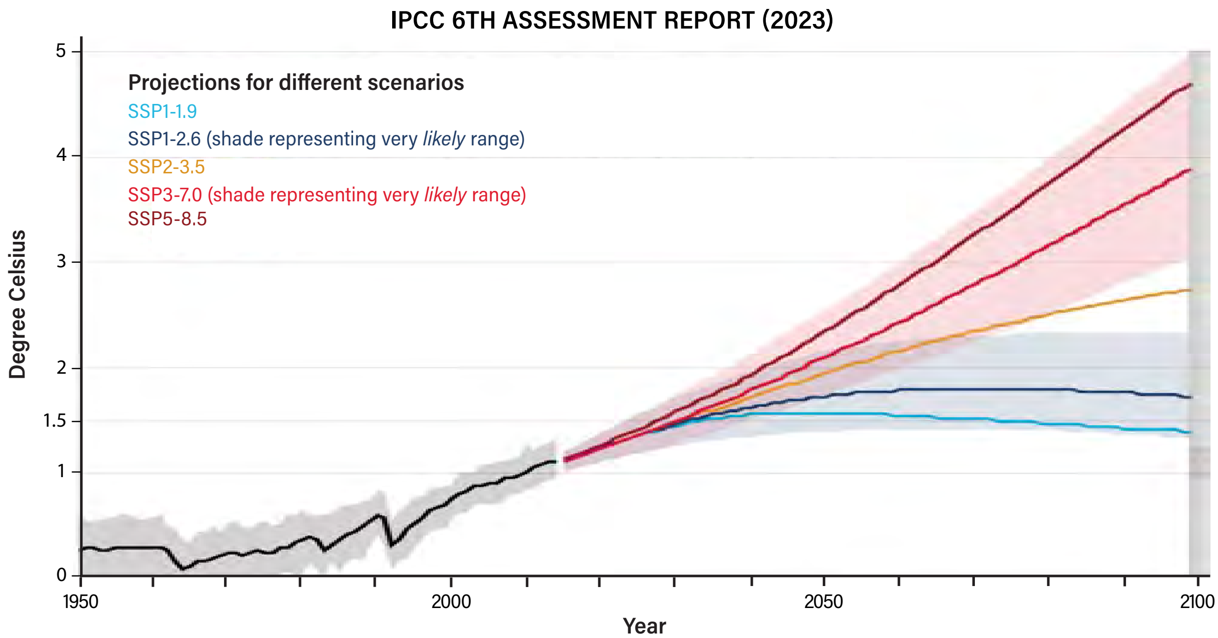

Figure 3. Temperature history and potential future trends.[7]

The IPCC 6th Assessment Report states that "human-induced climate change, including more frequent and intense extreme events, has caused widespread adverse impacts and related losses and damages to nature and people, beyond natural climate variability."[8] Furthermore, the report indicates (with high confidence) that "the rise in weather and climate extremes has led to some irreversible impacts as natural and human systems are pushed beyond their ability to adapt."[9] Figure 4 shows a projection of the number of days per year where combined temperature and humidity conditions pose a mortality risk to individuals for different warming scenarios.

As shown in Figure 4, even at 3° C, some regions will experience temperatures above what is considered highly dangerous levels to human activity and performance for as long as half of the year or longer. Such extreme temperatures will affect human and equipment performance. The DoD must plan and adapt to this reality today.

Climate change also manifests in the form of rising sea levels. According to the National Oceanic and Atmospheric Administration (NOAA), the two major causes of global sea level rise are thermal expansion caused by ocean warming (since water expands as it warms) and increased melting of land-based ice, such as glaciers and ice sheets.[10] The global average sea level has risen 8-9 inches

7. Figure 3 Source and Enhanced Description: Figure 3 identifies the likely temperature trends the earth may experience. Socio-economic trends are built into the underlie scenarios that drive climate models. As stated by the IPCC, the IPCC is neutral regarding the assumptions underlying the SSPs but references them to ensure traceability amongst the existing literature. SSP3-7.0 is the scenario that projects a 3 to 4.5°C increase in temperature above pre-industrial levels. (Source: IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.)

8. IPCC, Summary for Policymakers, Climate Change 2022: Impacts, Adaptation, and Vulnerability, Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge, UK and New York, NY: Cambridge University Press, 2023), 9, https://doi.org/10.1017/9781009325844.001.

9. IPCC, Summary for Policymakers, Climate Change 2022: Impacts, Adaptation, and Vulnerability, 9.

10. Rebecca Lindsey, "Climate Change: Global Sea Level," NOAA, April 19, 2022, https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level.

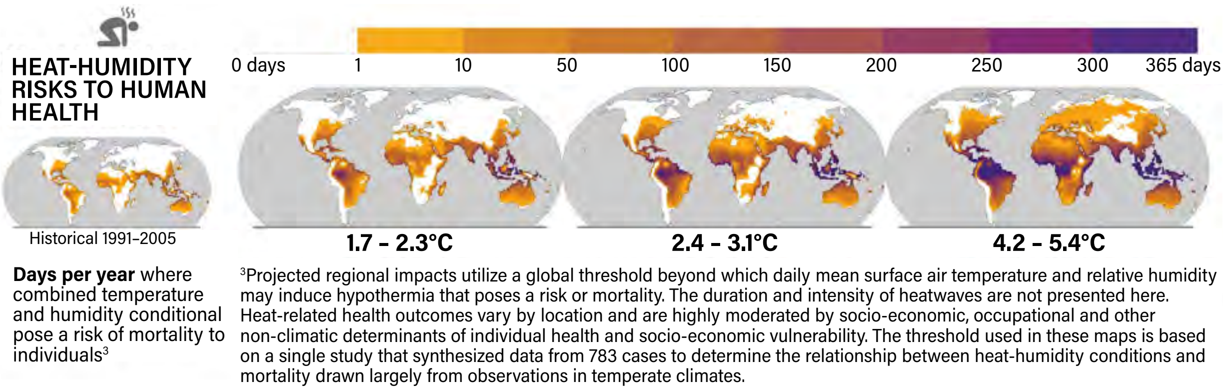

Figure 4. Heat-humidity risks with climate average increases.[11]

(21-24 centimeters) since 1880 and the rate of global sea level rise has more than doubled from 0.06 inches (1.4 millimeters) per year throughout most of the twentieth century to 0.14 inches (3.6 millimeters) per year from 2006-2015.[12] Significant wave height has increased since the 1950s over much of the North Atlantic.[13] Furthermore, a recent study published in the journal Nature states that, "Results indicate the upper-ocean warming, a consequence of anthropogenic global warming, is changing the global wave climate, making waves stronger."[14] Factors such as these could have severe implications for DoD base resilience and operational readiness in the future and will be discussed in detail in the Force Readiness section of this report.

Another manifestation of climate change is the increased incidence of regional droughts and higher evapotranspiration rates. As indicated with high confidence by the IPCC 6th Assessment Report, changes in water balance in the atmosphere driven by warming can lead to drought in some areas and an increase in moisture in others.[15] Figure 5 shows a world map of changes to soil moisture for a 4°C global warming scenario.

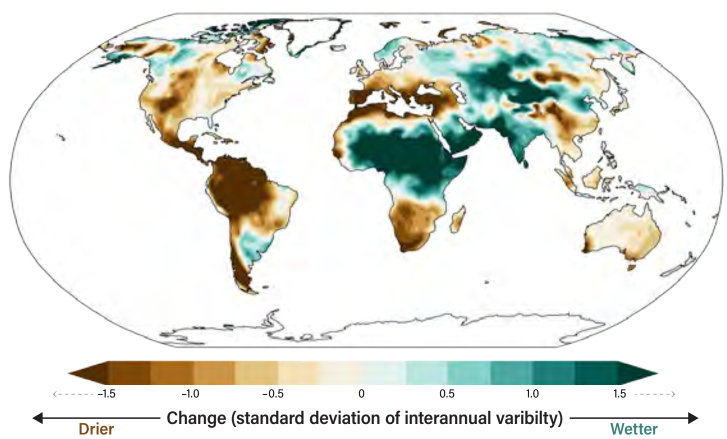

Figure 5. Annual mean total column soil moisture change (standard deviation).[16]

11. Figure 4 Source: IPCC, 2023: Longer Report. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.)

12. Lindsey, "Climate Change: Global Sea Level."

13. M. Rhein et al., Observations: Ocean, In: Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge, UK and New York, NY: Cambridge University Press, 2013), 258, https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter03_FINAL.pdf.

14. Borja G. Reguero et al., "A recent increase in global wave power as a consequence of oceanic warming," Nature Communications 10, no. 205 (Jan. 2019): 1, https://doi.org/10.1038/s41467-018-08066-0.

15. IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge, UK and New York, NY: Cambridge University Press, 2023) 3–32, doi: 10.1017/9781009157896.001.

16. Figure 5 Source: Figure SPM.5 in IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

Under such a scenario, northern Africa and southern Europe, for example, would receive significantly less precipitation, as would much of the North and South American continents. This DSB report looks at the implications of such conditions and how the DoD can adapt and respond to these future realities.

Additional Considerations Regarding Climate Change

As we delve deeper into the implications of climate change on global security, it becomes evident that this challenge is multifaceted. The earth is a complex system, so climate change (in its most general meaning) is not an isolated phenomenon but rather part of a complex interplay involving many factors that extend beyond the emission of greenhouse gases (GHGs), as shown in Figure 6. In many regions, deforestation, urbanization, and land subsidence (e.g., due to ground aquifer depletion) have local impacts that can also be significant. For example, coastal flooding in some areas is due more to coastal subsidence than rising sea levels. Forest fires may be as much a result of where people live and changes in forest management as it is to changing climate patterns. The reduction in high altitude aerosols (which is, in part, a consequence of reduced air pollution) has a complex effect on climate, with different, localized impacts. While the warfighter may only be concerned with the aggregate impact, understanding the relative contributions of these diverse causes helps us better predict the timing of climate changes and better plan the rate and pace of needed adaptation and mitigation.

Additional societal factors play a significant role in amplifying or tempering the indirect risks of climate change. These societal catalysts encompass a broad spectrum, including economic considerations, population changes, resiliency measures, and government corruption. As with the direct causes of climate change, understanding the intricate causal pathways is pivotal for making the most informed predictions and crafting effective responses.

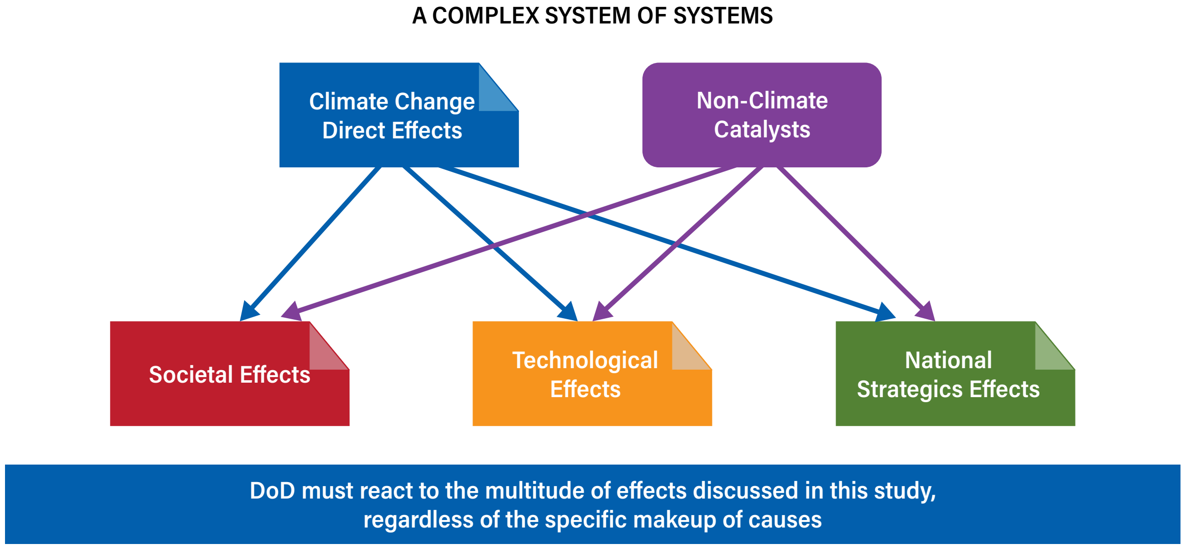

Figure 6. Cross system impacts and influences.

Of course, the Department of Defense and the United States, more broadly, must react to both climate change's environmental effects and the indirect effects it may induce. We emphasize these indirect effects occur only in conjunction with the political, social, and economic changes affecting our world. We also note the relative impact of different factors is immensely variable. For example, temporal and regional or country-specific changes in governmental capability, population growth, resource overconsumption, and rapidly evolving land-use policies may combine in varying degrees with changes to the climate to cause stresses on populations, changes in migration, hostility, and more. Very specifically, no presenters to the Board argued that climate change was the primary causal factor in population migration today. Still, all felt it might be a contributor whose importance increases in the future.

Today, the impact of climate change extends its reach across the globe, with approximately 3.3 to 3.6 billion people residing in areas highly vulnerable to its effects.[17] The regions experiencing the most adverse impacts include Africa, Asia, Central and South America, small island nations, and the Arctic. These vulnerable areas, often characterized by their susceptibility to extreme weather events and environmental degradation, underscore the urgency of this study and the imperative to act swiftly and decisively.

It is also important to note that not all the broader effects of climate change are adverse. Some regions may benefit because of climate improvements or because they possess materials necessary for climate-induced demands for raw materials. An additional effect of climate change is the technological impetus to enable renewable power, nuclear and fusion energy, the hydrogen economy, electrification, battery storage, and other zero-carbon emission technologies. These technological changes are happening because of the global need to reduce greenhouse gas emissions and are likely to change the technologies warfighters use to fight.

Climate Change Science: Gaps in Knowledge

We must also acknowledge the inherent gaps in our scientific knowledge in our pursuit of understanding climate change and its profound ramifications for global security. While the scientific community continuously advances its understanding of climate change through Global Circulation Models/Global Climate Models (GCMs) and innovative research, specific critical gaps persist. GCMs have made significant strides in projecting the future of our planet's climate for specific GHG emission scenarios. Still, substantial uncertainties remain, particularly regarding the interplay between climate change and natural climate variability at the regional scale.[18] These models do not address the necessary DoD-relevant operational spatial and timescales, specifically in the crucial 1-10-year range and at the regional level. This knowledge gap, coupled with a shortage of sufficient data to fully understand the nuanced interactions and feedback loops within the earth's coupled land, sea, and atmosphere system, hinders our capacity to foresee and prepare for short to medium-term climate-induced events that could impact military operations and readiness. These gaps are exacerbated when attempting to downscale global climate change models to make accurate predictions at the regional scale. As shown in Figure 7, while GCMs provide valuable insights into global trends, they often require more granularity and high-resolution historical climate data for precise regional predictions. Of note in this context is the advent of exascale computing, which enables global climate model computing at finer resolutions down to a few-kilometer scale for limited timescales of 1-3 years.[19] While this scientific development is promising, it remains constrained by access to exascale computing resources worldwide.

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17. IPCC, Summary for Policymakers, Climate Change 2022: Impacts, Adaptation, and Vulnerability, 12.

18. IPCC, Technical Summary, In: Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge, UK and New York, NY: Cambridge University Press, 2023), 117, https://doi.org/10.1017/9781009157896.002.

19. David Bader, "Lawrence Livermore National Laboratory: Climate Modeling for Climate Change Prediction," (Presentation to DSB, SA Inc. Executive Conference Center, Arlington, VA, June 21, 2023).

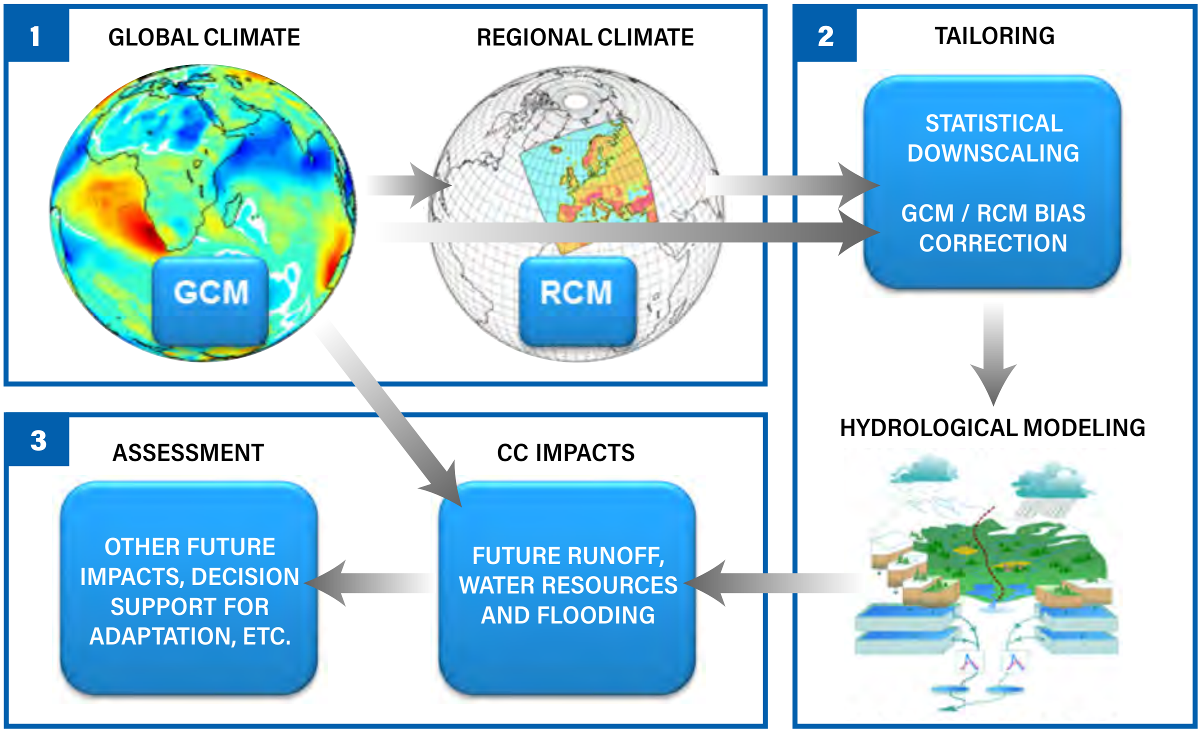

Figure 7. Modeling Chain.[20]

These knowledge gaps leave an incomplete picture of how climate change will manifest over time in specific geographic areas and collectively impair the Department of Defense's ability to make climate-informed operational and readiness decisions. As the DSB stands at the intersection of science and security, the Board recognizes that the Department's response to climate change must be underpinned by what is understood to be the most accurate knowledge available.

Section Summary

In this report, the DSB seeks to unravel the intricate tapestry of climate change's effects on global security. The study aims to diagnose challenges and prescribe innovative solutions and strategies that will fortify U.S. national security and ensure U.S. military readiness worldwide.

The Board's consensus is that a first step for the Department is the establishment of a dedicated Climate Planning Cell to serve as the nexus for climate-related data collection, simulation, strategy development, and coordination across DoD and with other federal and civilian agencies. This single joint entity is envisioned to consolidate various Department of Defense efforts engaged in developing and applying climate models and projections while collecting and disseminating climate and weather data for use across the defense establishment, including for Combatant Commands' warfare simulations and forecasts. Further, the Climate Planning Cell would interface with organizations across the Research & Development (R&D) community, the Interagency, and others to leverage their diverse expertise and resources to mitigate risk and enhance resilience.

The Board also emphasizes an immediate and sustained effort to prepare for expanded temperature

20. Figure 7 Source: Lawrence Livermore National Laboratory, 2023.

variances throughout the projected regions of operations. This study occurred in 2023, the year of the warmest global ambient temperatures ever recorded. As discussed above, since the advent of the industrial age, global temperature trend lines have an overall increasing trend. There is no reason to expect this global temperature rise to slow markedly, and since higher ambient temperatures create more extreme weather events, storms, hurricanes, and moisture differentials should be an ever-increasing expectation.

Higher temperatures, more expansive operational areas, more moisture combined with more severe droughts, and more drastic extreme weather events demand that DoD service personnel and equipment are prepared for these extremes. Equipment must have a lifecycle commensurate with these extremes—from seawater inlet temperatures to Wet Globe Bulb Thermometer readings for the service member. Personnel recruiting, conditioning, training, and equipping must be similarly governed by the environmental conditions of a rapidly changing future.

With higher global temperatures and the eventuality of service personnel deployments to the thawing Arctic, protecting personnel from biological and physiological hazards takes on higher importance. Most vector-borne tropical diseases, novel viruses, and over half of the known human pathogenic diseases are aggravated by climate change.[21] Eukaryotic viruses revived from ancient permafrost present an entirely unknown threat to humans and plant life. Preparing our forces for many of these unknowns must include near-continuous force monitoring in threatened areas. R&D for infectious disease monitoring and human performance in extreme environments is vital.

Extreme weather conditions, rising sea levels, soil subsidence, and the effects on infrastructure will cause the Department to take more resilient measures to shore up our facilities worldwide. Funding for this activity is sparse, and there are many political pressures. The Defense Science Board encourages a more realistic assessment of which facilities may be too hazarded to be maintained, which facilities warrant early reconstruction to a higher standard, and in which communities our service member families and assorted contractors live and therefore need to be included in DoD's resilience efforts. Further, innovative technology exists to monitor DoD facilities in situ continuously. The combination of climate-threatened facilities, the advent of new technologies that obviate the compelling need for some facilities, and the cost-to-mission increase because of infrastructure challenges lead the Board to suggest that this process may substantially impact the Department's global footprint.

Since weather extremes may alter the defense posture of both Allies and potential adversaries, weather manipulation could be weaponized. The threat of state-sponsored large-scale weather manipulation using geoengineering techniques warrants an Allied ability to detect such actions.

Standalone power sources were discussed extensively in multiple areas of this study. From establishing a remote Arctic base to providing emergency power at expeditionary forward operating facilities, the Board believes the Department has a significant role in normalizing the adoption and regulation of so-called micro nuclear reactors at the small power range.

Despite the imperative of a global effort to confront climate change, nationalistic and non-state actor agendas have heightened geopolitical tensions. This friction is an added barrier to international cooperation and collective action. For example, the technological demands that emerge from the desire to mitigate climate change have sent a more heightened demand signal for an array of critical

21. Camilo Mora et al., "Over half of known human pathogenic diseases can be aggravated by climate change," *Nature Climate Change* 12, (2022): 869-875, https://doi.org/10.1038/s41558-022-01426-1.

materials often found in areas of significant strife. Consequently, international relations have altered in the recent past as competition for new relationships has sharpened to achieve favorable business arrangements. The Board believes additional effort must be placed on ensuring the U.S. has a long-term view in building future relationships in these areas.

The United States Department of Defense stands at a critical juncture. Facing a long-established mandate to provide domestic and international security, it must now confront the multifaceted challenges posed by a changing climate. The Board believes the U.S. can confidently navigate the future through significant international engagement, strategic investments in raw materials, processing, and manufacturing of advanced technologies, and enhanced training paradigms in preparing our service personnel.

The contributions of the Board's study members and the collaborative efforts across agencies underscore the Department's collective resolve to address the security implications of a changing climate. As we look ahead, the adaptability, innovation, and foresight demonstrated by DoD and its personnel will be pivotal in safeguarding national security in an era of unprecedented environmental change.

The report is divided into five sections. The first section analyzes the relationship between climate change drivers and increased global geopolitical stresses and tension. In the second section, the report explores the current state of climate change models and data, climate education, and the emergence of potential climate-altering strategies. It outlines the Board's findings and recommendations. The third section of the report lays out extensive findings and recommendations related to force readiness. In section four, the report focuses on the issue of supply chains and critical resource competition and lays forward a set of findings and recommendations related to these issues. In the fifth and final section, the report analyzes the current state of global climate diplomacy and recommends actions that the DoD can take to work with Allies and partners in mitigating the impact of climate change on global security.

Geopolitical Stability and Domain Challenges

Overview

Global warming generates vastly different Earth system responses. The IPCC 6th Assessment Report states, "With every increment of global warming, regional changes in mean climate and extremes become more widespread and pronounced."[22] As shown in Figure 8, land areas warm more than oceans, and high latitudes warm more than the tropics.

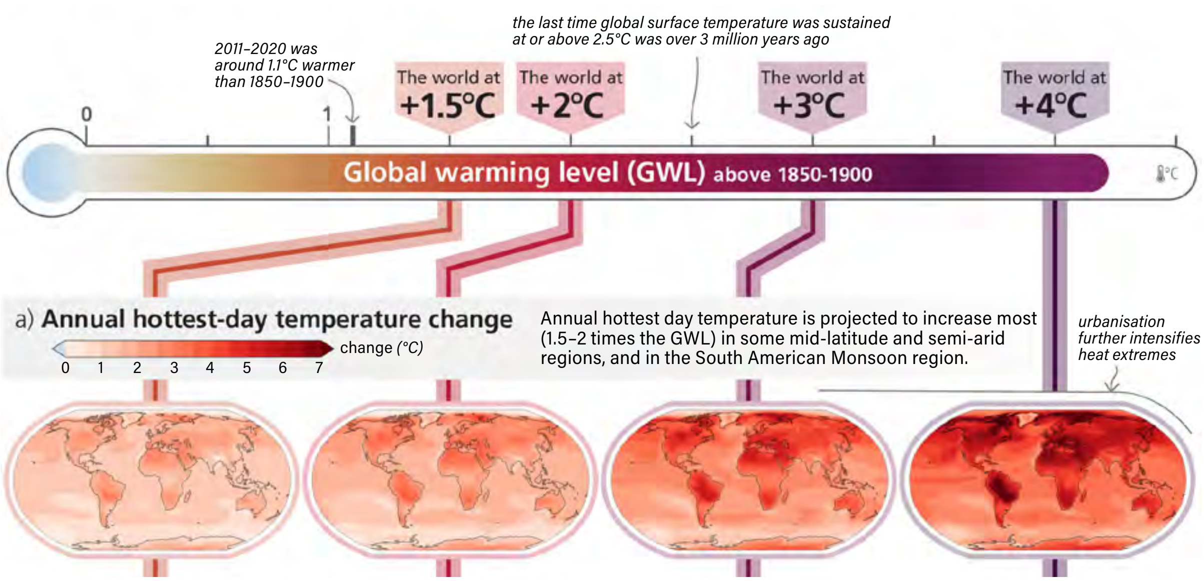

Figure 8. Projected changes of annual daily maximum temperature.[23]

As discussed in the next chapter, there is tremendous uncertainty about the future course of climate change, particularly regionally, and much will depend on what mitigation measures are undertaken. However, modeling and simulation of a wide range of possible future scenarios make clear that major impacts, including dangerously higher temperatures, extreme drought, and severe flooding in various areas of the globe, are now "baked in" even in the more optimistic scenarios.[24]

22. IPCC, *Climate Change 2023: Synthesis Report*, 14.

23. Figure 8 Source: IPCC, *2023: Summary for Policymakers. In: Climate Change 2023: Synthesis Report. A Report of the Intergovernmental Panel on Climate Change. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Geneva, Switzerland: IPCC, 2023), 1-34, doi: 10.59327/IPCC/AR6-9789291691647.001.

24. IPCC, *Climate Change 2023: Synthesis Report.*

Additionally, climate-driven tipping points, such as a potential slowdown of the Atlantic Meridional Overturning Circulation (AMOC) and the Gulf Stream, could alter global weather patterns in ways that will severely disrupt where and how humanity lives. The IPCC 6th Assessment report has indicated that while "there is medium confidence that the Atlantic Meridional Overturning Circulation will not collapse abruptly before 2100," it is "very likely to weaken over the 21st century" due to climate change.[25] A recent National Aeronautics and Space Administration (NASA) study added that "the movement of water north and south throughout the Atlantic might be weakening due to climate change," with potentially severe consequences for weather patterns in Europe.[26]

As discussed in the introduction, the impact of climate change across different regions will depend on how well those regions adapt, which, in turn, is a complex function of climatic and non-climatic drivers affecting those regions. The IPCC 6th Assessment Report states, "Multiple climatic and non-climatic risk drivers will interact, resulting in compounding overall risk and risks cascading across sectors and regions. Climate-driven food insecurity and supply instability, for example, are projected to increase with increasing global warming, interacting with non-climatic risk drivers such as competition for land between urban expansion and food production, pandemics and conflict."[27]

Climate-enhanced stresses alter geopolitical stability considerations and impact current and future U.S. global security interests. This report focuses on five world regions where climate stresses will directly impact global security interests and DoD readiness.

U.S. Homeland

Climate-induced events which lead to severe weather extremes in the U.S. Homeland can significantly impact the United States' ability to project power globally, potentially affecting military readiness, infrastructure, operational capabilities, and access to space. Past extreme weather events cost the U.S. military billions of dollars in cumulative damages. Addressing these challenges requires a commitment to adaptive strategies, resilient infrastructure, and investment in climate-proofing U.S. military facilities, whose long-term budgetary offsets and operational advantages present a compelling case for such investments.

Domain Challenges

The U.S. is well-positioned to confront and adapt to the challenges associated with the effects of a changing climate. This is because of the United States' relative wealth, its excellent natural resources, and its location in the middle latitudes, which means it is less affected by the extremes of climate change. That notwithstanding, climate change and related environmental events can undermine the U.S. military's ability to project power and maintain global security. Below are specific examples of these impacts.

Infrastructure Vulnerability:

- **Coastal Areas and Low-Lying Military Facilities:** Rising sea levels and severe weather events pose risks to critical naval installations. For example, Hampton Roads, Virginia, is home

25. IPCC, *Climate Change 2023: Synthesis Report*, 18, 78.

26. "Slowdown of the Motion of the Ocean," NASA, June 5, 2023, https://science.nasa.gov/earth/earth-atmosphere/slowdown-of-the-motion-of-the-ocean/.

27. IPCC, *Climate Change 2023: Synthesis Report*, 15.

to sixteen central military installations, including the world's largest naval base. This region is experiencing ground-level subsidence and rising sea levels, making it increasingly prone to flooding, consequent disruptions to operations and maintenance, loss of infrastructure, and a resulting potential of environmental damage. The vulnerability of billions of dollars of crucial materiel has a genuine potential to restrict military forces' ability to deploy to global contingencies. Likewise, extreme weather events could severely affect the U.S. Department of Defense and Intelligence Community's (IC) ability to reliably access space launch facilities, which are primarily located in vulnerable coastal areas.[28]

- **Training Facilities:** Wildfires and extreme heat can endanger training facilities and restrict the military's ability to conduct field training exercises. For instance, wildfires in expansive training facilities, such as California's Camp Pendleton, can have a significant negative effect on a unit's readiness-to-deploy status.

- **Cost to Facilities:** A recent example of largely unforeseen flooding phenomena caused by extreme weather, most likely amplified by climate change, is the high dollar repair of Offutt Air Force Base following a 2019 flood that damaged 137 base facilities, destroyed 118k square feet of Sensitive Compartmented Information Facility (SCIF) space, and displaced 3,200 personnel from their workplace.[29]

- **Military Whole Base Resiliency:** An important consideration of all military facilities is the supporting community, which hosts both service personnel and the supporting defense industrial base, schools, commercial activity, and quality of life features, which go hand-in-hand with the operating tempo of the base. This requires U.S. military investment within installations and consideration given to the surrounding community.

Health and Readiness of Personnel:

- **Heat Stress**: Increasing ambient temperatures and more severe heat waves can lead to more frequent heat stress conditions. Black Flag days, when the wet bulb globe thermometer readings indicate hazardous heat stress conditions exist, increasingly affect training. From 2008 to 2018, heat-related illness and associated lost training time cost the military nearly $1 billion.[30]

- **Extreme Weather:** Severe storms threaten infrastructure, operations of small craft and aircraft, especially helicopters, and space launch facilities. High wind conditions and prolonged drought lead to increasingly intense wildfires, often threatening military facilities but more frequently necessitating heavy use of the nation's National Guard. In California, a permanent task force was created to fight forest fires.[31] Other states have relied on their National Guard to aid in weather-related disasters, from wildfires to hurricane rescue operations.

28. Stephen Purdy Jr., (Presentation to DSB, Strategic Analysis Inc. Executive Conference Center, Arlington, VA, August 18, 2023).

29. Stephen Losey, "After massive flood, Offutt looks to build a better base," Air Force Times, Aug. 7, 2020, https://www.airforcetimes.com/news/your-air-force/2020/08/07/after-massive-floods-offutt-looks-to-build-a-better-base/.

30. Marc Kodack, "Heat-related illness increasing among U.S. military personnel," The Center for Climate & Security, August 30, 2019, https://climateandsecurity.org/2019/08/heat-related-illness-increasing-among-u-s-military-personnel/.

31. Joseph Clark, "Joint Task Force Rattlesnake: National Guardsmen Battle Wildfires in California," Department of Defense, July 20, 2023, https://www.defense.gov/News/Feature-Stories/Story/Article/3465349/joint-task-force-rattlesnake-national-guardsmen-battle-wildfires-in-california/.

Readiness Vulnerability in the Homeland: Florida

Florida hosts three Combatant Commands and over twenty military bases representing all branches of the U.S. military. It is one of the regions most at risk from extreme weather events most likely precipitated by climate change combined with subsidence. Eight of Florida's bases are ranked among the most vulnerable in the country, including Air Force bases such as Eglin, Hurlburt Field, Homestead, MacDill, and Tyndall, Patrick Space Force Base, Naval Air Station Key West, and the Blount Island Marine Corps Support Facility.[32]

- Northeast Florida, home to significant naval facilities like Naval Air Station (NAS) Jacksonville, Naval Station (NS) Mayport, and the Marine Corps Support Facility at Blount Island, faces threats from rising sea levels, flooding, hurricanes, and extreme heat. For instance, NS Mayport is at risk of inundation if struck by a Category 2 storm surge.
- Additionally, East Central Florida and the Treasure Coast, hosting crucial national security sites like Patrick Space Force Base, NASA, the Navy's Air Warfare Center's Ordnance Test Unit, and the Atlantic Undersea Test and Evaluation Center (AUTEC) complex, are susceptible to severe impacts from flooding, heatwaves, and rising seas, which could significantly disrupt military readiness and operations.
- A 2019 Senate Armed Service Committee hearing listed South Florida's Homestead Air Reserve base as one of the top 10 Air Force bases most at risk of impacts from severe weather events.[33]

U.S. Policy Concerns

- U.S. military installations most threatened by the effects of climate change will require expanded federal programs for mitigation and adaptation. The defense budget includes some funding to enact facility mitigation measures, but the cascading effects of climate change suggest these funding lines need to be revised. The most extensive existing federal mitigation program is the $500M/Fiscal Year (FY) "Building Resilient Infrastructure and Communities" program for hazard-prone areas. A $200M/FY "Flood Mitigation Assistance" program is specifically directed to flood-prone areas. These programs warrant consideration to be expanded.
- Base and facility repairs must reflect the expected lifecycle to account for future climate realities. The military often lacks congressional authorization to repair/replace weather-damaged infrastructure to a higher structural standard. The Services and their base commanders must contend with repair funds that only repair to an 'as was' status—shifting to a lifecycle approach, with an expectation that climate change will worsen, may be a more cost-effective approach.

32. Stephen Lee, Paul Murphy, Atthar Mirza, and Jon Meltzer, "Rising Seas Imperil US Sites, Military Bases, Worth $387 Billion," https://news.bloomberglaw.com/environment-and-energy/rising-seas-imperil-us-sites-military-bases-worth-387-billion; Ben Watson and Patrick Turner, "These Are the US Military Bases Most Threatened by Climate Change," Defense One, June 12, 2019, https://www.defenseone.com/threats/2019/06/these-are-us-military-bases-most-threatened-climate-change/157689/.

33. Watson and Turner, "These Are the US Military Bases Most Threatened by Climate Change."

- Costs associated with climate-proofing facilities may have significant budget offsets. A proactive approach can lead to considerable cost savings for U.S. taxpayers, especially considering the increasing frequency and intensity of climate-related disasters. Furthermore, climate-proofing can include integrating renewable energy sources and energy-efficient technologies, reducing the carbon footprint of these facilities and creating lower operational costs over time. Reducing dependence on external energy supplies will enhance the self-sufficiency and operational readiness of the military. While the upfront costs of climate-proofing military facilities are notable, the long-term budgetary offsets and operational advantages present a compelling case for such investments.

Indo-Pacific

The Indo-Pacific Command (INDOPACOM) region's vulnerability to climate changes, especially sea level rise, high wind weather patterns, and the frequency and intensity of typhoons has ushered in a new era of challenges. The imperative to adapt to these changes offers a pivotal moment for the United States to enhance its security posture while fostering resilience against the threats posed by a changing climate.

Geopolitical Concerns

Top geopolitical concerns in the Indo-Pacific include:

- **Potential for increased humanitarian needs and Humanitarian Assistance and Disaster Relief (HADR) operations:** The INDOPACOM region is highly vulnerable to sea level rise and more frequent extreme weather. Consequently, the number and complexity of HADR missions may increase concomitantly. A confluence of sea level rise, subsidence, and, in some cases, population increase, has combined to limit the ability to cope with the effects of climate change in outlying locations. Most affected are land/sea/air operations in forward operating areas such as Guam, the Marshall Islands, and Palau.

- **A geopolitical alignment of nations could block, contest, and/or disrupt the global effort to mitigate climate change.** Additional efforts must be undertaken to be proactive with most at-risk nations since many cannot build the resiliency needed to confront rising sea levels and more ferocious storms. This presents an opportunity for the DoD to solidify relationships by assisting in resilience efforts.

- **Manipulation of water availability:** Restricting access to water is an age-old technique to impose one nation's will on another. More significant variances in water flow due to climate perturbations, population growth, urban migrations, and industrial demand have become a geopolitical challenge, especially in coastal communities. A key geographical risk is in the Mekong Delta. China's manipulation of water sources/flows from the Mekong and the Qinghai-Tibetan Plateau results in significant stresses on Mekong downstream communities' vital access to water and food. This "Mekong crisis" affects the water supply to the Mekong's 300 million people downstream of China. The river supports one of the world's largest inland fisheries and is vital to the region's prolific agriculture industry. Upstream dam construction, unsustainable water management, and overuse of resources are on the rise, which makes the rise in sea level especially challenging for the region.

A Case Study for Global Security

The Mekong Delta is also emblematic of broader challenges facing river basins worldwide. Issues such as transboundary water management, the impact of climate change on freshwater resources, and the intersection of water scarcity with food security and migration are global in scope. Learning from the Mekong experience can inform policies and strategies to address complex challenges posed by water scarcity in other regions, emphasizing the importance of sustainable resource management, international cooperation, and proactive conflict prevention strategies.

Figure 9. Tibetan rivers within Tibetan Plateau, at risk due to climate change and foreign influence.[34]

Domain Challenges

Top domain challenges in the Indo-Pacific include:

- **Vulnerability to climate change, especially sea level rise, high winds, typhoon frequency and intensity:** The most critical issue is sea level rise, which threatens low-lying atolls like Kwajalein in the Marshall Islands. Other island nations and coastal communities are especially vulnerable to the increased intensity of weather extremes due to climate change.
- **Non-aligned nations are increasingly vulnerable to China's trade and security measures:** China has considerable influence over Southeast Asian countries' domestic and foreign

34. Figure 9 Source: Michael Buckley, "Meltdown in Tibet."

policies. This leverage can be used to align these nations with China's stance on climate policies, fossil fuel use, and environmental policies, which often run counter to global mitigation strategies.

Diplomatic Challenges

Chinese influence in the INDOPACOM region presents an ongoing challenge to the United States, particularly in the context of climate-induced events and broader climate security:

- **Strategic Resource Competition**: The climate variables alter the availability and distribution of fresh water and arable land, straining regional relationships and introducing a range of contingencies that encompass resource-driven tensions.
- **Infrastructure and Presence**: China's financing of infrastructure projects gives it an outsized presence in a highly charged strategic landscape.
- **Humanitarian Assistance and Disaster Relief**: Climate change is expected to increase the frequency and severity of natural disasters in the region. China's growing capability and willingness to provide HADR could bolster its soft power and influence at the expense of the United States, especially if the DoD and U.S. government are perceived as less responsive or effective in these situations.

By addressing these diplomatic challenges comprehensively, the DoD can help mitigate the risks posed by climate change and work to reduce Chinese influence in the INDOPACOM region. The Board recommends:

- **Enhanced Resilience**: The DoD should invest in making its bases and infrastructure in the INDOPACOM region more resilient to climate change, including fortifying facilities against severe weather events and integrating renewable energy sources to reduce supply chain vulnerabilities.
- **Strategic Partnerships**: Strengthening alliances and partnerships by collaborating on climate security initiatives, shared infrastructure projects, and HADR training.

Polar Regions

Climate change, combined with competing strategic interests, has increased activity levels and geopolitical tensions in the Polar Regions. The high latitudes present unique domain challenges in which technological advancements and presence may strengthen the U.S. security posture in the region. Furthermore, the Arctic is estimated to contain about 90 billion barrels of undiscovered oil and 1,669 trillion cubic feet of natural gas, which constitutes a substantial portion of the world's undiscovered conventional resources.[35] Russia has announced significant investments to tap into these resources, planning a $300 billion project to explore and develop Arctic oil and gas reserves.[36]

35. "Arctic oil and natural gas resources," U.S. Energy Information Administration, Jan. 20, 2012, https://www.eia.gov/todayinenergy/detail.php?id=4650.

36. Julian Turner, "The cold thaw: inside Russia's $300bn Arctic oil and gas investment," Offshore Technology, May 4, 2020, https://www.offshore-technology.com/features/the-cold-thaw-inside-russias-300bn-arctic-oil-and-gas-investment/.

Geopolitical Concerns

Key geopolitical concerns in Polar Regions include:

- **Adversaries treat polar regions as core strategic interests and assert sovereignty in these regions.**
  - Russia removed Arctic references of "constructive international cooperation" pledges with the intent to militarize the region and establish closer cooperative ties with non-Arctic states who "pursue a constructive policy towards Russia."[37]
  - China has declared its intent to implement its Global Security Initiative, which includes the "Polar Silk Road," potentially expanding Russia's Northern Sea Route.
  - There is also potential for overlapping Arctic seabed claims between Russia, Denmark, Canada, and Norway – all of which have jurisdiction over an exclusive economic zone (EEZ) below the Central Arctic Ocean. Complicated demarcations are underway that may lead to international arbitration or conflict between competing nations.
- **Adversaries cooperate and collude in these regions and assert economic influence.**
  - Expanded security collaboration amongst U.S. adversaries in the polar region, notably the signing of an Arctic region security agreement between China and Russia in April 2023, has introduced a series of potential risks exacerbated by a warming, more accessible Arctic.
  - China appears to have set the stage for constructing a class of nuclear-powered icebreakers.

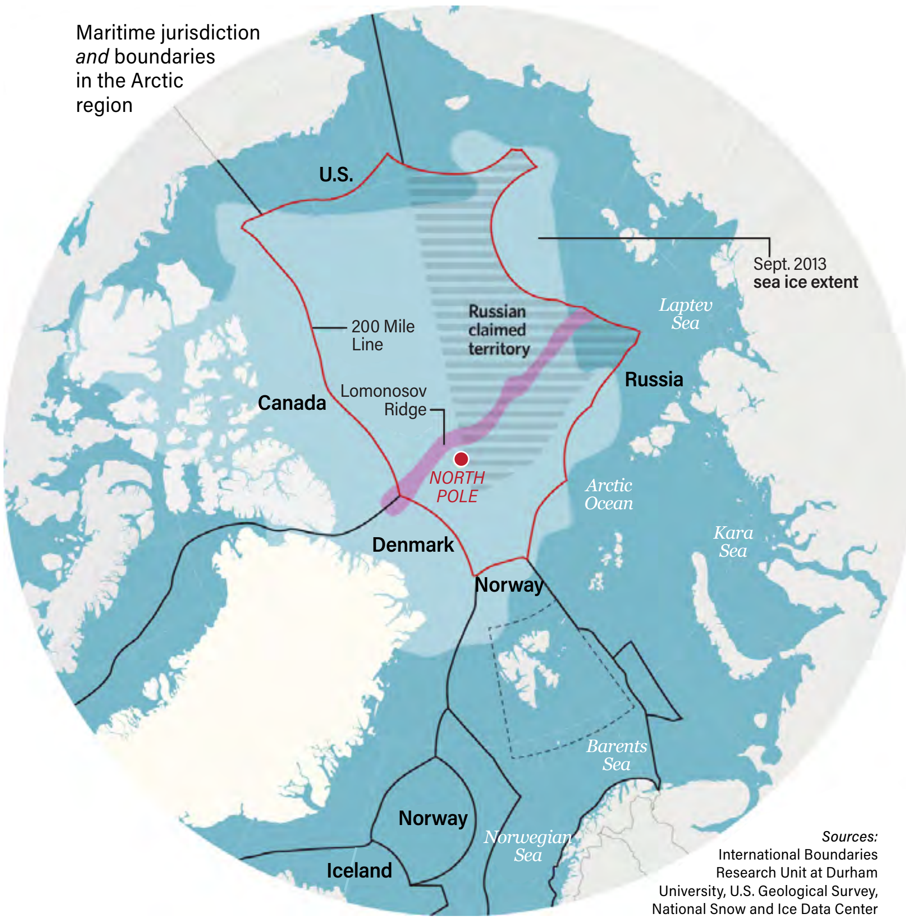

Figure 10. International claims in the Arctic.

37. Nikita Lipunov and Pavel Devyatkin, "The Arctic in the 2023 Russian Foreign Policy Concept," The Arctic Institute, May 30, 2023, https://www.thearcticinstitute.org/arctic-2023-russian-foreign-policy-concept/.

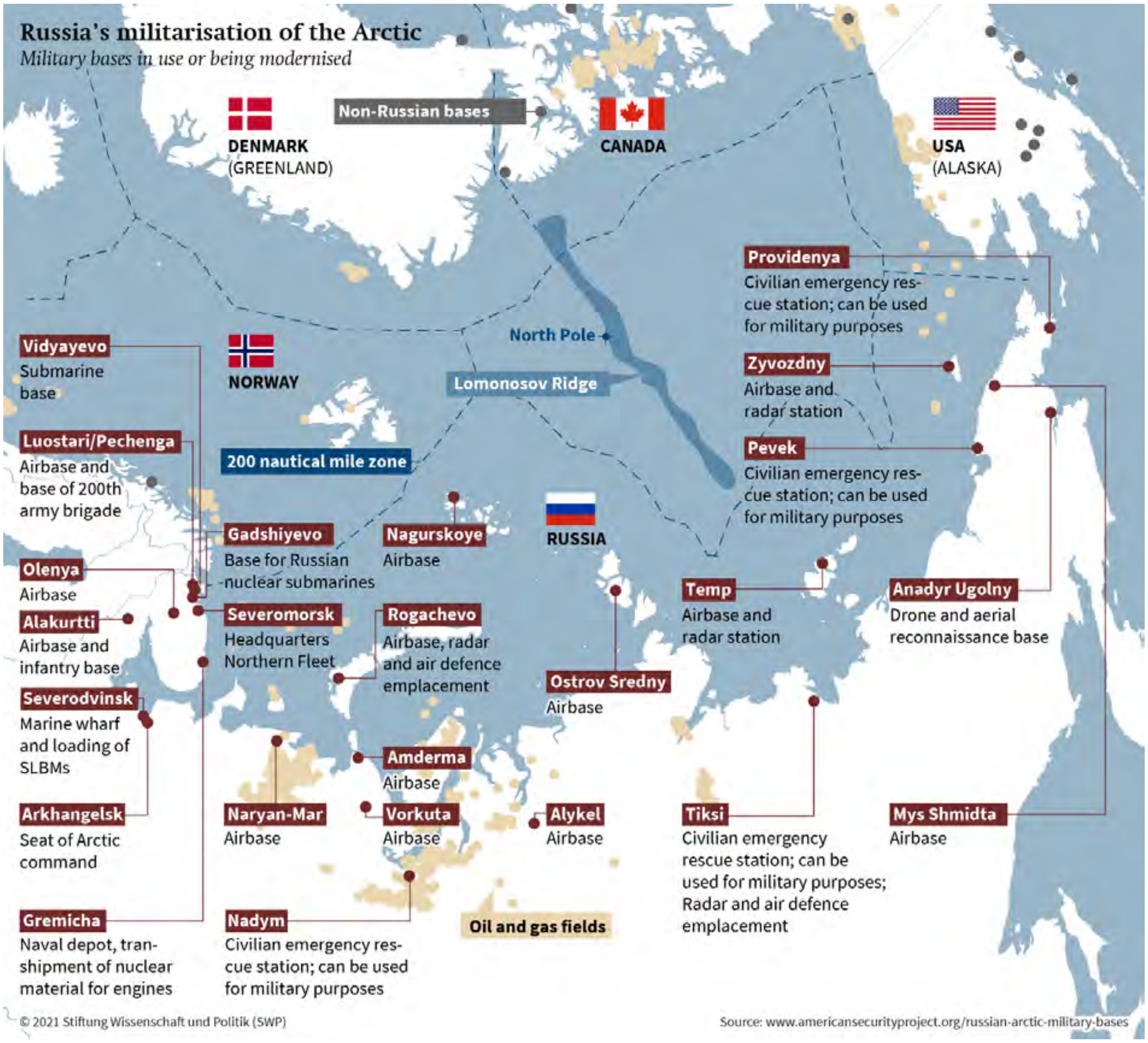

Figure 11. Expansion of Russian militarization.[38]

Domain Challenges

The polar regions present domain challenges for military operations, in particular:

- **Electromagnetic environment affecting sensor and military communications system performance.**
- **Ice aggregation and ship stability and surveillance.**
- **Navigation accuracy challenges in the high latitudes.**
- **Dynamic sea-land-ice boundaries impact radio waves and surveillance performance due to ducting and clutter.**

38. Figure 11 Source: Michael Paul and Göran Swistek, https://www.swp-berlin.org/10.18449/2022RP03/.

The combination of these factors—electromagnetic disruptions, navigation challenges, ice accumulation on exposed equipment, and complicated radio wave ducting—makes operating in polar regions exceptionally demanding. It requires specialized equipment and strategies to maintain effectiveness in these harsh and rapidly changing environments.

Diplomatic and Defense Challenges

The polar regions, with their unique strategic and environmental significance, present myriad diplomatic and defense challenges, such as:

- **A New Operational Environment**
  - Power generation and logistics for remote operations.
  - Weapon, surveillance, and communication systems idealized for the high latitudes.
- **Diplomatic Negotiation, Treaty Integrity, and Defense Posture**
  - Competing U.S. and Ally imperatives.
  - Different priorities—scientific exploration, environmental protection, resource exploitation—compete within Arctic nations and with other international parties.

Africa

Climate change disproportionally impacts Africa, where it overwhelms adaptive capacity and exacerbates instability, multiplying existing political unrest, violent extremist organization (VEO) activity, and malign influence. Lack of access to large swaths of the continent at the scale necessary to assist in a climate-induced calamity warrants a broader international effort to enact resiliency measures in the most affected regions. In significant portions of Africa, feeble infrastructure, great distances, significant heat challenges, lack of potable water, disease, hunger, and a burgeoning population challenge even a consortium of like-minded nations and aid agencies to tackle the problem.

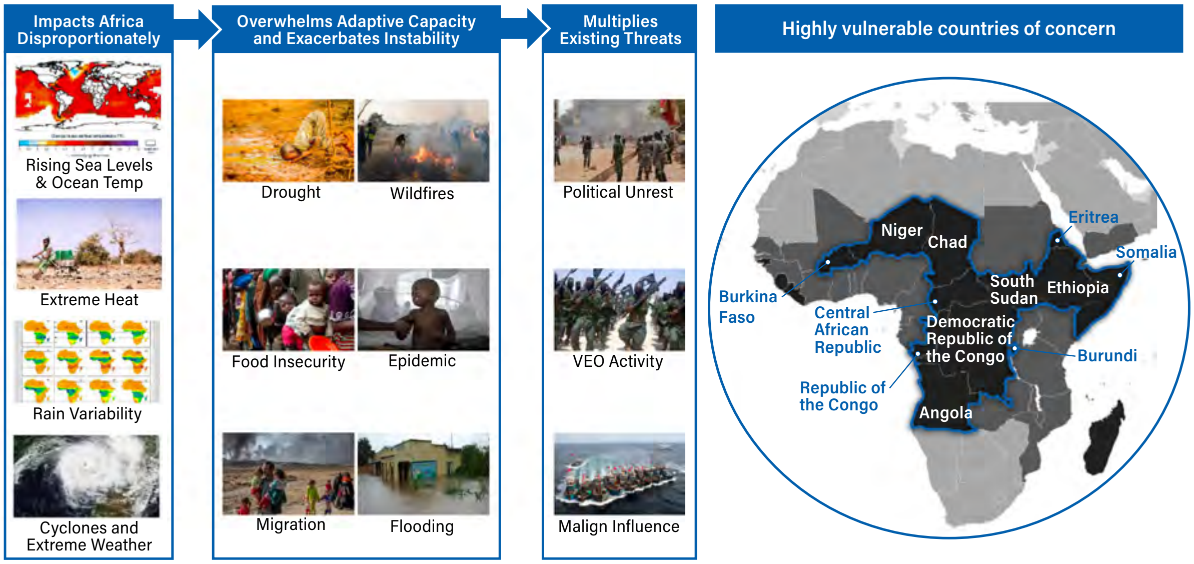

Figure 12. Growing negative effects of climate change on Africa.[39]

39. Figure 12 Source: USAFRICOM.

Geopolitical Concerns

Climate change is slowly reshaping the geopolitical landscape of Africa:

- **Intensified Diplomatic, Military, and Security Activities:** China and Russia have extensive security and military activities with African states or subnational movements that include military, paramilitary (including private military companies such as the Wagner Group and its subsidiaries), and police organizations to sustain regimes in power. The rise of mercenary groups, such as the Wagner Group in the Sahel, amidst the backdrop of climate-induced instability exemplifies the complex challenges faced by the U.S. military.

- **Increase in Migration:** Climate change acts as a catalyst for displacement and migration, particularly when other compounding factors such as water scarcity, rapid population growth, poverty, extreme weather events, and land inundation (which undermine health and livelihoods) are at play. In many cases, unregulated migration has broad implications for regional security and poses a humanitarian challenge for the U.S.

- **Water Conflict in Major African River Basins:** The Nile, Niger, and Congo River(s) are lifelines for the majority of Africans. Transboundary water disputes and localized cooperative water management failures have ongoing potential for violence that is amplified by climate change.

Although the U.S. military has a minor role in adaptation strategies, it can implement its security assistance programs, various training and exercise initiatives, and regional partnerships to help build a nation's resiliency.

Domain Challenges

Top domain challenges in Africa include:

- **Reduced U.S./Allied presence in conflict zones:** The reduced U.S./Allied presence in Africa is epitomized by France's abandonment of its security operations in the Sahel region in 2023.[40] This, combined with a growing sense of unease for terrorism, proxy forces, and feeble governmental institutions, and as climate change pushes living standards downward, highlights much of the problems in the Sahel and Somali regions. Future risks to stability include:
  - **Criminality and Terrorism**: The Sahel region has become a hotbed for extremist groups such as Boko Haram, Al-Shabaab, and affiliates of the Islamic State of Iraq and Syria (ISIS) and al-Qaeda.[41] These umbrella groups run criminal enterprises based on migration, trade, and sales of national resources. Although not a direct effect of climate change, the second-order effects plaguing the region for centuries become more pronounced with greater weather extremes.
  - **Strategic Rivalries**: The lack of resources during rapid changes in weather patterns weakens the ability of elected leaders to provide for a growing population, thereby opening the possibility for undue external influences antithetical to U.S. strategic interests. China and Russian proxies have filled this role in multiple Sahel nations.

40. John Irish and Edward Mcallister, "West losing sight of Sahel after France announces Niger withdrawal," Reuters, Sept. 25, 2023, https://www.reuters.com/world/west-losing-sight-sahel-after-france-announces-niger-withdrawal-2023-09-25/.

41. Jason Warner and Charlotte Hulme, "The Islamic State in Africa: Estimating Fighter Numbers in Cells Across the Continent," *Combatting Terrorism Center Sentinel* 11, no. 7 (2018), https://ctc.westpoint.edu/islamic-state-africa-estimating-fighter-numbers-cells-across-continent/.

Spotlight on Major African River Basins

- **Nile River Basin:** The Nile River, spanning ten countries and home to around 300 million people, is the subject of significant conflict, primarily between Egypt, Ethiopia, and Sudan.[42] The conflict mainly revolves around water rights and the use of the river's resources, with historical treaties dating back to the colonial era heavily favoring Egypt and Sudan over upstream countries like Ethiopia. The construction of Ethiopia's Grand Renaissance Dam has escalated tensions, with Egypt fearing a reduction in its water supply.[43] The Nile Basin Initiative, established in 1999, aims for cooperation, but the region continues to face challenges in reaching a fair and sustainable management solution. The People's Republic of China (PRC) has increased its infrastructure, trade, and diplomatic support for Ethiopia, whose dispute with Egypt around the Grand Ethiopian Renaissance Dam (GERD) places Egypt's agriculture at risk due to the parties' inability to agree on the water release rate.[44]

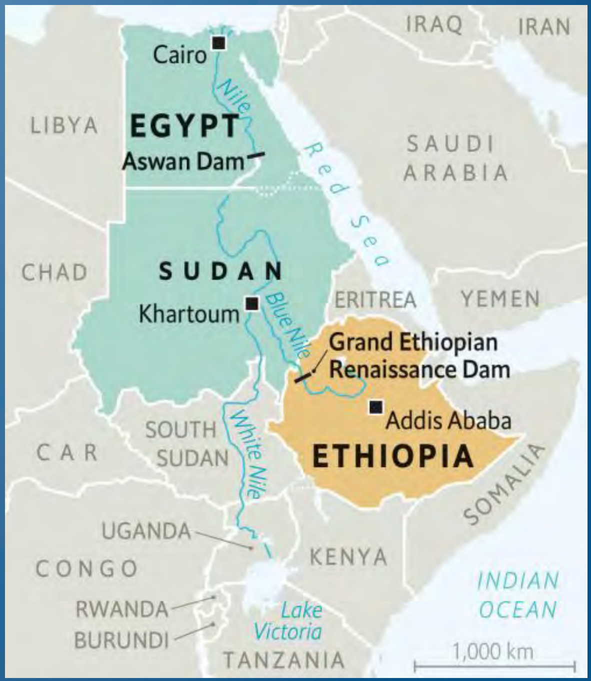

Figure 13. Grand Ethiopian Renaissance Dam. (Source: The Economist, 2020)

- **Niger River Basin:** Covering 2.2 million km² and extending into ten countries, the Niger River is a crucial water source for approximately 100 million people.[45] The region has experienced significant climate variability, affecting water availability and quality, leading to tensions over resource management and access.

- **Congo River Basin:** The PRC has also moved aggressively to cement its relationship with the government of the Democratic Republic of Congo (DRC).[46] The DRC is home to the Congo River Basin, the second largest after the Amazon. The climate crisis and water stress impact the basin's vast water resources and are a key driver of regional migration and conflict.

- **Escalation of Herder and Planter Conflicts:** Climate change aggravates herder-planter tensions, particularly in regions where changing rainfall patterns and desertification disrupt traditional livelihoods.[47] These conflicts often arise from competition over land and water resources, exacerbated by environmental degradation, climate change, and population growth.[48] For the U.S., addressing these conflicts requires a strategic blend of humanitarian aid, development assistance, and conflict resolution efforts to address the root causes of climate-induced tensions and support sustainable agricultural practices and livelihood diversification.

- **Piracy and Maritime Security**: Population growth, low-lying land subsidence, and rising sea states combined with illegal fishing have made the Gulf of Guinea a dangerous place for piracy. Pollution of fisheries and rising sea temperatures also threaten livelihoods, leading to social unrest and violence.

- **Humanitarian Crises and Mass Migration**: Climate change is exacerbating droughts, famines, and conflicts over resources in Africa, leading to humanitarian crises, displacement, and migration.

- **Limited Capacity Building**: The U.S. and its Allies have been working to build the capacity of African militaries to support good governance and human rights. These programs are vital for the long-term stability and security of the continent in challenging climate-change environments.

- **Chinese attempts to dominate the African critical minerals supply chain.** China's efforts pose challenges to U.S. military readiness and commercial businesses in several ways:

  - **Impact on DoD Readiness**: China now dominates minerals for a wide array of military technologies, including advanced electronics, satellite communication systems, and weapons platforms.[49] Many of these minerals and their associated processing are crucial to the energy industry.

  - **Climate and Environmental Concerns**: The aggressive extraction and processing of critical minerals can harm the local environment, contributing to pollution, habitat destruction, and water scarcity. These environmental impacts can undermine regional stability by displacing communities and fueling conflict over dwindling natural resources. Moreover, China's dominance in this sector might prioritize extraction efficiencies over environmental protections, further aggravating climate-related challenges in the region.

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42. "The Nile River Dispute From Ethiopia's Perspective," Geopolitical Futures, Feb. 14, 2020, https://geopoliticalfutures.com/the-nile-river-dispute-from-ethiopias-perspective/.

43. "The bitter dispute over Africa's largest dam," The Economist, July 4, 2020, https://www.economist.com/middle-east-and-africa/2020/07/04/the-bitter-dispute-over-africas-largest-dam.

44. Jonathan Gorvett, "China in the middle of Nile mega-dam feud," Asia Times, July 31, 2021, https://asiatimes.com/2021/07/china-in-the-middle-of-nile-mega-dam-feud/.

45. Marisa Goulden and Roger Few, *Climate change, water and conflict in the Niger river basin*, (International Alert and University of East Anglia, 2011), 5, https://www.international-alert.org/publications/climate-change-water-and-conflict-niger-river-basin/.

46. David Uren, "How China wrested control of the Congo's critical minerals," The Strategist, Australian Strategic Policy Institute, December 6, 2021, https://www.aspistrategist.org.au/how-china-wrested-control-of-the-congos-critical-minerals/; H.R. 4548: To require a national strategy to secure United States supply chains involving critical minerals sourced from the Democratic Republic of the Congo, and for other purposes. https://www.congress.gov/118/bills/hr4548/BILLS-118hr4548ih.pdf; Gracelin Baskaran, "A Window of Opportunity to Build Critical Mineral Security in Africa," Center for Strategic & International Studies, October 10, 2023, https://www.csis.org/analysis/window-opportunity-build-critical-mineral-security-africa.

47. MS Evans and B Munslow, "Climate change, health, and conflict in Africa's arc of instability," Perspect Public Health 141, no. 6 (Nov 2021): 338-341, doi: 10.1177/17579139211058299.

48. Jarso Mokku, "Climate Change Destroys the livelihoods of Keyan pastoralists," United Nations: Africa Renewal, January 4, 2023, https://www.un.org/africarenewal/magazine/january-2023/climate-change-destroys-livelihoods-kenyan-pastoralists.

49. Xianbin Yao, "China Is Moving Rapidly Up the Rare Earth Value Chain," Brink, Aug. 7, 2022, https://www.brinknews.com/china-is-moving-rapidly-up-the-rare-earth-value-chain/.

- **Economic and Technological Dependence**: Control over the critical minerals supply chain translates into economic and technological dependence. This dependence could hinder global efforts to combat climate change if access to these essential materials becomes a tool for geopolitical coercion, limiting the adoption of green technologies and slowing the transition to a low-carbon economy.

- **Severe temperature extremes in Africa present significant operational challenges for the U.S. military and its Allies and partners in the region**, affecting equipment reliability, human performance, and physical wellness.
  - **Equipment Reliability and Maintenance:** High temperatures often degrade the performance of military equipment, from vehicles and aircraft to personal gear and electronic devices, necessitating more frequent maintenance and replacements. The U.S. could provide its partners with advanced cooling systems, heat-resistant materials, and technology designed to operate in extreme conditions, ensuring that military assets remain operational even in the harshest environments.
  - **Human Performance:** Extreme heat significantly affects military personnel's effectiveness, increasing the risk of heat-related illnesses and reducing cognitive and physical capabilities. The U.S. can supply wearable cooling technologies, hydration systems, and climate-controlled mobile shelters that help maintain troops' effectiveness during operations. Training programs on heat acclimatization and medical readiness can also be shared to enhance partner forces' resilience to temperature extremes.
  - **Physical Wellness:** Long-term exposure to severe heat can have adverse health effects on military personnel, affecting their overall readiness and operational capacity. The U.S. could offer advanced medical technologies and support systems, including portable medical kits equipped with heat stress monitors and treatments for heat-related conditions. Additionally, constructing infrastructure with improved living and working conditions can help mitigate the health impacts of temperature extremes.
  - **Training and Capacity Building:** Security assistance and engagement programs can expand to include medical preparedness and equipment maintenance. They should also include water management and rule of law/human rights training.
  - **Research and Development Collaboration:** Collaborating on research and development projects focused on innovations in materials science, cooling technologies, and sustainable solutions in extreme weather conditions can lead to mutually beneficial advancements. These collaborations can foster technological exchange and development tailored to the specific needs and challenges faced in the African environment.

By providing advanced technologies and support to partner militaries, the U.S. could not only enhance the operational effectiveness of its partners in Africa but also strengthen diplomatic ties and security cooperation, demonstrating a commitment to mutual security and stability in the region. This approach aligns with broader strategic objectives of building resilient alliances and partnerships capable of collectively addressing the challenges posed by climate change and extreme weather conditions.

Diplomatic and Defense Challenges

Africa presents a complex tapestry of climate change-related diplomatic challenges set against a backdrop of growing adversarial influence, humanitarian demands, and regional collaboration on climate issues. For example:

- **Adversarial Influence and Climate Vulnerabilities:** The strategic expansion of adversaries such as China and Russia into Africa is not just a matter of security collaboration and commercial engagement but also intersects with climate vulnerabilities. With its Belt and Road Initiative, China has invested heavily in infrastructure projects across Africa, encompassing transportation, telecommunications, and energy sectors. These investments often come with security agreements, providing a framework for military training, arms sales, and intelligence sharing. Conversely, Russia has focused more on military and security engagements, including arms sales, military training, and private security contractor agreements. Both nations use these collaborations to strengthen their global influence and secure strategic footholds, while African countries benefit from economic and security assistance. As African nations increasingly position themselves as key partners in climate adaptation and mitigation efforts, they will require further investments to address climate-induced challenges. Against the backdrop of China having thus far been the dominant funding partner for many African nations, the U.S. will face the diplomatic challenge of countering this adversarial influence by integrating climate considerations into its security partnerships, ensuring that its approach to military cooperation and assistance also addresses the pressing climate needs of African nations.

- **Humanitarian Demands and Climate Disasters:** The burgeoning African population is especially affected by severe droughts and devastating floods. Difficult or underdeveloped logistical infrastructure often amplifies the demand for international humanitarian assistance and response. Emergency relief supply facilities, long-term resilience and infrastructure development, and investment in local capacity efforts are ongoing, but significant gaps remain. The U.S. military's role in Humanitarian Aid and Disaster Relief is limited due to scale and range considerations. Still, when called upon, the U.S. military becomes a tool to foster goodwill and strengthen bilateral and regional ties. This approach underscores the importance of viewing humanitarian outreach as an integral component of climate diplomacy.

- **Collaboration on Climate Issues:** Collaborative efforts on climate adaptation and sustainability can be a powerful diplomatic tool for the U.S., aligning its military and security engagements with broader environmental goals. This collaborative stance offers a pathway to mitigate the security implications of climate change, such as resource conflicts and displacement, while enhancing partnership opportunities with African nations. It also positions the U.S. as a leader in climate security.

Latin America

Latin America also emerges as a critical theater where climate-induced events could have multifaceted impacts on regional stability and international security. The United States and the broader global community face challenges in this area as environmental shifts intersect with energy security concerns, the strategic recalibrations of adversarial powers, and the infrastructural vulnerabilities of pivotal assets like the Panama Canal. It explores how these dynamics are redefining defense and diplomatic strategies, necessitating a nuanced approach to hydro diplomacy and fostering robust inter-American collaboration to address long-term implications of climate change and ensure regional resilience and the preservation of U.S. and global security interests.

Geopolitical Concerns

Examples of geopolitical concerns that collectively underscore the complex environment the U.S. navigates to safeguard its interests and regional stability in Latin America include:

- **Energy security risks associated with China advancing its dominance across supply chains of critical minerals** in Latin America for the global energy transition.
  - **Dependence on Critical Minerals**: The U.S. increasingly relies on critical minerals like nickel, copper, lithium, and cobalt for the global energy transition, especially for technologies like electric vehicle batteries and renewable energy systems. China's dominance in Latin American supply chains for these minerals poses a significant energy security risk to the U.S. If China restricts access to these essential minerals, the U.S. could face challenges in achieving its clean energy goals.
  - **Supply Chain Vulnerability**: China's control over critical mineral supply chains in Latin America could give it the ability to influence market prices, create shortages, and exert geopolitical leverage.
- **The Rise in Chinese influence in Latin American trade** has seen a corresponding decrease in U.S. influence in select nations. Figure 14 below highlights the shift in commercial trade for South American nations. Figure 15 lists specific investments China has made with a variety of South American nations. This becomes problematic in climate change efforts to preserve rainforests and transition to a lower carbon future, for instance.

Figure 14. Shifting dominance in Latin America.[50]

50. Figure 14 Source: Kavya Beheraj/Axios, https://www.axios.com/2021/09/23/china-influence-latin-america-trade-biden.

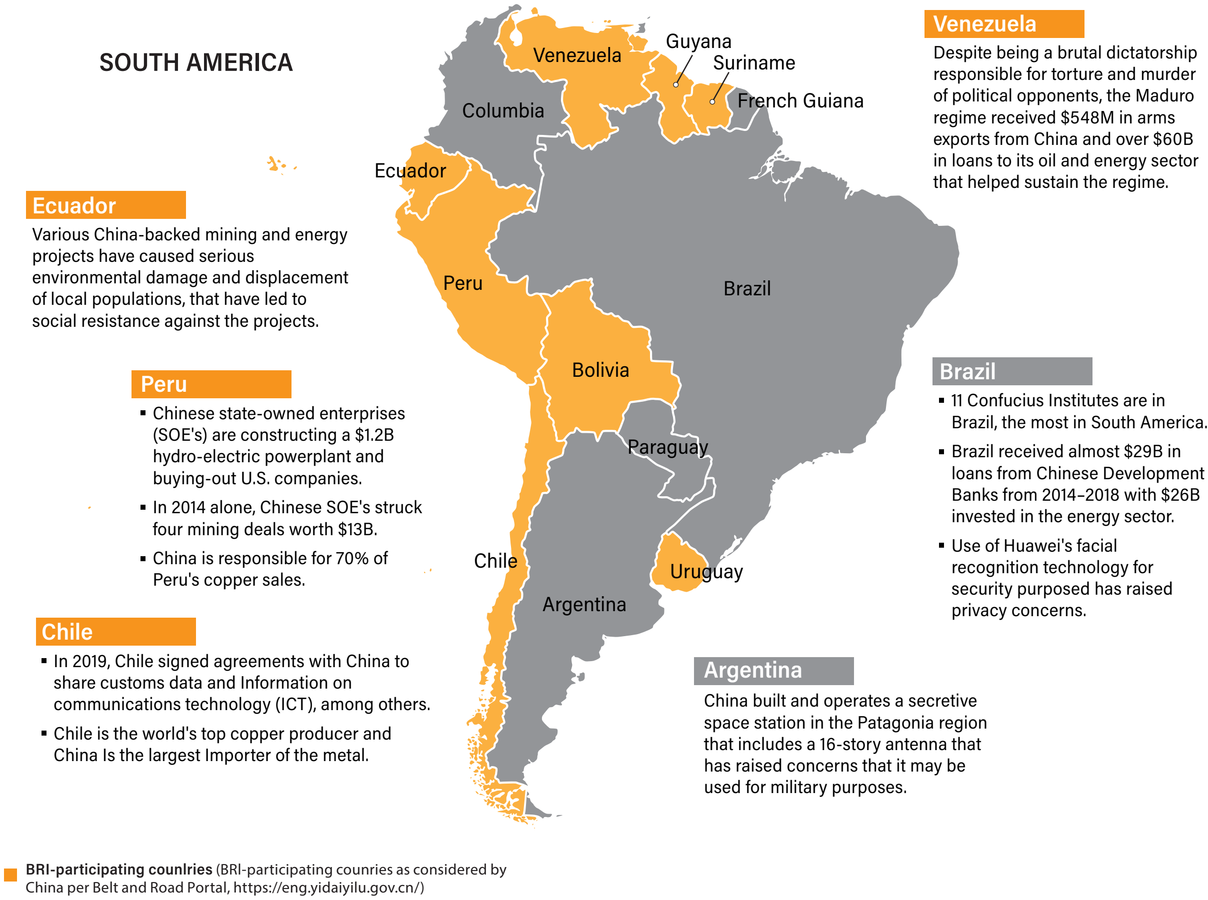

Figure 15. Increasing Chinese influence in Latin America.[51]

Domain Challenges

- **The Panama Canal is at risk due to sustained drought conditions and excessive commercial traffic**, which have combined to cause turmoil in global shipping. With over 200 vessels waiting at both entrances and since over 70% of cargo moving through the canal comes to or goes from the United States, sustained droughts without concomitant reductions in ship traffic through the canal are causing supply chain challenges in the U.S.[52] Alarmingly, such droughts are becoming increasingly commonplace, and larger ships with greater drafts further complicate the ramifications of less water available in the canal.

- **Sustainment of food production capabilities for Latin America's growing population** is a multifaceted challenge exacerbated by climate change impacts.

  – Alterations in ocean currents due to rising global temperatures can lead to unpredictable weather patterns. Ocean currents are integral in regulating climate; changes in these patterns can result in extreme weather conditions like droughts or floods. For example, the El Niño Southern Oscillation, which affects the Pacific Ocean currents, directly impacts rainfall

51. Figure 15 Source: House Foreign Affairs Committee.

52. Costas Paris, "The Panama Canal Has Become a Traffic Jam of the Seas," The Wall Street Journal, Aug. 18, 2023, https://www.wsj.com/business/logistics/panama-canal-drought-causes-traffic-problems-ecd9d335.

distribution in Latin America. An increase in the frequency and intensity of El Niño events, as projected by climate models, could lead to prolonged drought periods in some areas and excessive rainfall in others, disrupting traditional farming cycles.

- Climate change is expected to exacerbate environmental challenges, such as soil degradation and water scarcity. As temperatures rise, rainfall patterns shift and the tropical glaciers of the Andean region melt, the traditional agricultural zones in Latin America may experience reduced crop yields. This is particularly alarming in a region where most of the population relies on subsistence farming. Reduced yields threaten food security and economic stability, and they cause unrest in rural and indigenous communities that depend on agriculture as their primary source of income.
- As shown in Figure 16, melting of the Andean glaciers poses a threat to water supplies and agriculture in countries such as Chile, Peru and Bolivia.
- Finally, the impact of climate change on marine ecosystems directly affects fisheries, a crucial food source for many Latin American countries. Changes in ocean temperatures and currents can lead to the migration of fish stocks to cooler waters, reducing local fish populations and impacting the livelihoods of coastal communities.

GLACIERS IN THE ANDES ARE MELTING, CREATING FOOD STRESS AND POLITICAL UNREST AMONGST INDIGENOUS POPULATIONS

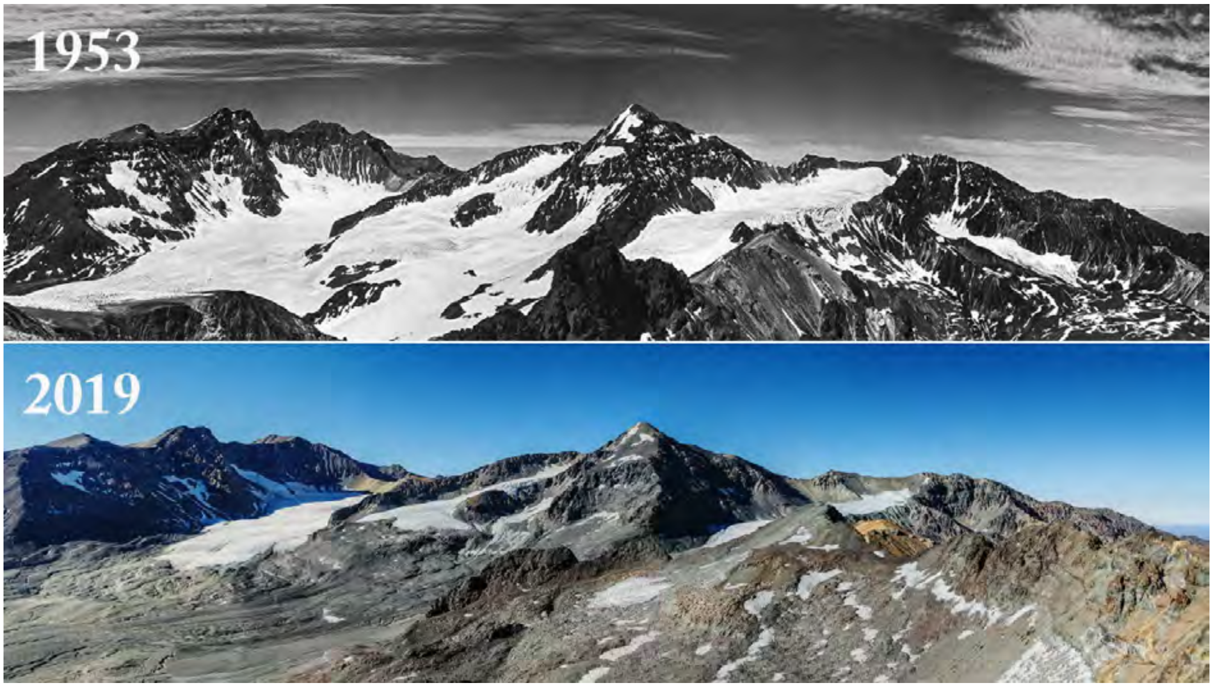

Figure 16. The Olivares Alfa glacier in Chile has lost 66% of its ice mass since 1953.[53]

53. Figure 16 Source: Louis LIiboutry, Alex Cattan, and Marc Turrel, https://e360.yale.edu/features/andes-meltdown-new-insights-into-rapidly-retreating-glaciers.

Diplomatic and Defense Challenges

- **The dependability of the Panama Canal to flow military forces between the Atlantic and Pacific is a substantial planning factor**; right now, the water level is low; four years ago, there was significant flooding and climate change predictions showed more precipitation in the years ahead. Addressing this variability and possible scenarios is critical. Rising sea levels, unpredictable weather patterns, and shifting ecosystems threaten the Panama Canal's operations. In this context, continued inter-American collaboration is paramount to address the pressing imperative of the canal's environmental conservation and safeguard this vital conduit for global trade and U.S. military forces.

- **U.S.-Mexico hydro-diplomacy has become increasingly intricate, giving rise to a complex array of associated water-governance challenges.** Shared water resources, like the Colorado River and the Rio Grande, are crucial for both nations but are increasingly strained under the pressures of prolonged droughts, rising temperatures, and a dramatically changed riparian system. Negotiations over water rights and allocations are becoming more complex as both countries grapple with the need to satisfy agricultural, urban, and environmental water demands. Climate change intensifies these challenges, underscoring the urgency for collaborative and sustainable water management strategies between the U.S. and Mexico.

Section Summary

Climate change presents profound geopolitical stability and domain challenges that significantly impact U.S. military readiness and operations across various regions, including the Homeland, Indo-Pacific, the Polar Regions, Africa, and Latin America, as well as affecting U.S. Allies and partners in these regions.

In the Homeland, rising sea levels, extreme weather events, and extreme temperatures threaten troop readiness and vital military infrastructure, necessitating costly climate-proofing measures.

The Indo-Pacific region poses operational challenges due to its strategic significance and vulnerability to climate-induced disasters like typhoons and sea-level rise. This region affects geopolitical dynamics, especially with China's growing influence.

In the Polar Regions, melting ice opens new strategic frontiers, complicating defense and security operations due to harsh environmental conditions and necessitating specialized equipment and strategies.

Due to climate change, Africa and Latin America face increased resource scarcity and humanitarian crises. This could potentially lead to instability and conflict, which can challenge U.S. military engagements and humanitarian missions.

Additionally, climate change impacts the operational capabilities and strategic positioning of U.S. Allies and partners, requiring coordinated global response and adaptation strategies.

Resilient infrastructure, sustainable energy sources, and adaptive military strategies are imperative to maintaining operational effectiveness and geopolitical stability in the face of these escalating climate challenges.

Climate Situational Awareness and Decision Support

Overview

To respond effectively to climate change, the DoD must have a deep understanding of its possible impacts on military forces. This section provides findings and recommendations regarding the current state of the DoD's assessment of the nature and magnitude of climate change risks and the strategies that might be deployed to mitigate those risks. It also examines the state of climate education and training in the DoD. Imparting specific and current knowledge about how climate change will impact regional stability, military operations (including humanitarian and disaster relief operations resulting from climate change effects), logistics, and bases and installations to military decision-makers and planners is critical to the effectiveness of the DoD's response.

Climate intervention (also referred to as "geoengineering") has also been studied as a potential option to mitigate and counteract the effects of climate change, both locally and across a region. Depending on how climate intervention is carried out, it could have significant implications on military operations and global security. In addition, the ability to detect ongoing climate intervention by state and non-state actors is essential from an awareness perspective and in the event a military response is required.

Climate Models and Data

State of the Science

Figure 17 illustrates the accuracy of the weather and climate forecasting over time based on today's state-of-the-art models. Over short time scales of a few hours to a few days, weather models can be highly predictive. On the other extreme, global climate models (GCMs) provide forecasts of the state of the global climate over decadal timescales, but only with significant uncertainties. As can be seen in Figure 18, DoD operational plans and timelines are often formulated at six-month to ten-year time scales where neither current weather models nor GCMs provide useful information to the war planner. Current climate model forecasts do not consider current conditions and should not be regarded as accurate on these timescales. Weather models are limited in their predictive timelines and do not fully consider climate impacts. In addition to targeting these timescales, operational planners will require higher resolution predictions and the incorporation of tailored models of local systems such as agriculture, water scarcity, and populations. As illustrated in Figure 17, sub-seasonal to seasonal and seasonal weather predictions are key, and while good progress is being made in the development of these models, much work is still needed in this space. It should be a priority of the climate and weather community, including the DoD, in the future.

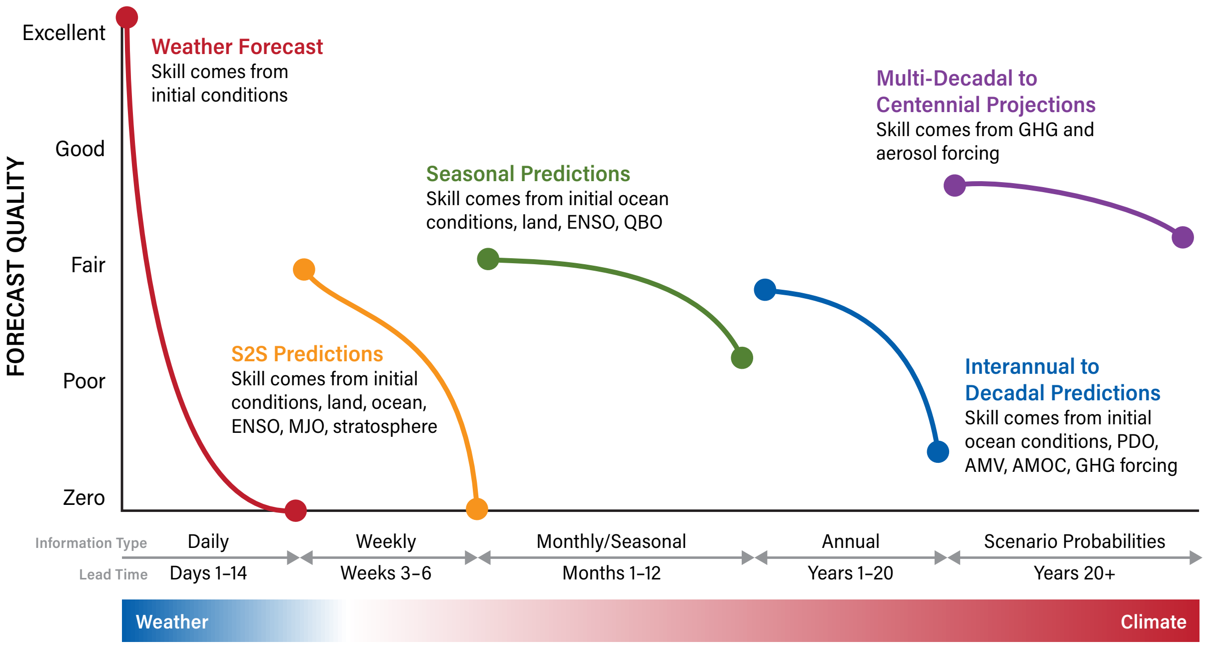

Figure 17. Forecast quality across timescales for various weather and climate prediction models.[54]

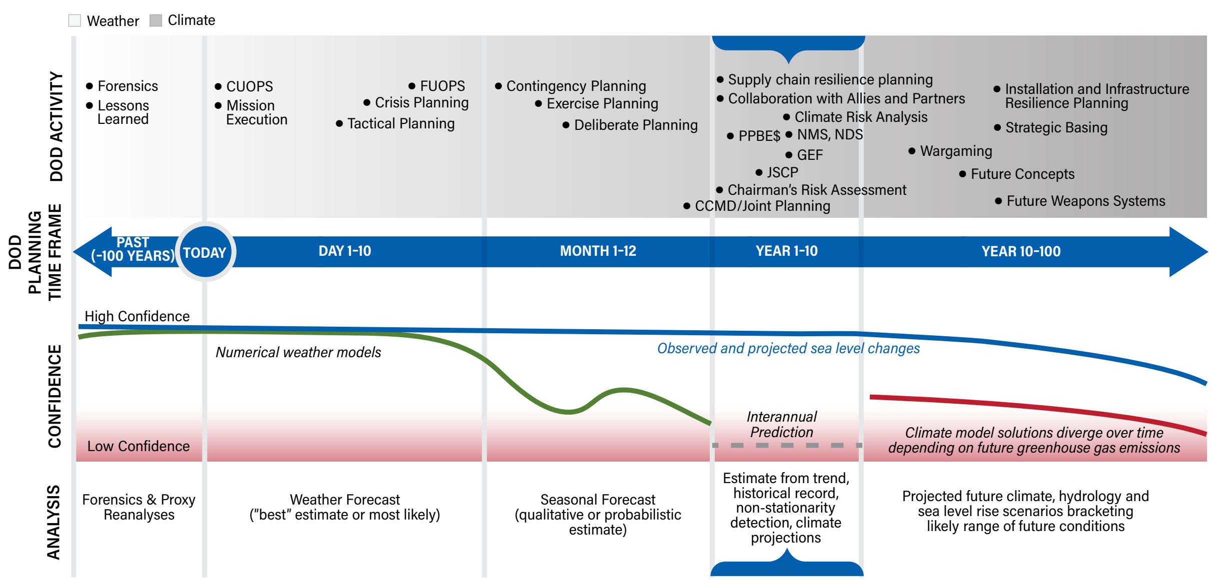

Figure 18. Illustration of the gap in model-based predictions of climate and weather risk relative to DoD operations planning timeframes.[55]

54. Figure 17 Source: Professor Kathy Pegion, School of Meteorology, University of Oklahoma

55. Figure 18 Source: DSB adaptation of figure provided by the Office of the Assistant Secretary of Defense for Energy, Installations, and Environment, Presentation to DSB, February 15, 2023; Figure 18 Acronyms: CUOPS: Current Operations; FUOPS: Future Operations; PPBE: Planning, Programming, Budgeting, and Execution Process; NMS: National Military Strategy; NDS: National Defense Strategy; GEF: Guidance for Employment of the Force; JSCP: Joint Strategic Capabilities Plan

A variety of GCMs and ensembles offer the current gold standard and are used by the IPCC to estimate climate risk.[56] Among these are the Coupled Model Intercomparison Project (CMIP), including CMIP5 and CMIP6. CMIP5 is used in DoD climate tools such as the DoD Climate Assessment Tool (DCAT), while the IPCC used CMIP6 in its latest climate report and projections. The Department of Energy (DOE) supports efforts to increase the computational power and resolution of climate models, such as the Energy Exascale Earth System Model (E3SM) project, which includes recent advances in resolving cloud systems, among others.[57]

Integrated assessment models, such as the Global Change Analysis Model (GCAM) developed by Pacific Northwest National Labs (PNNL), dive further into the details of human activity and interactions with the Earth system.[58] These models typically deal on global scales with low geospatial resolutions but can be used to consider economic factors.

Regional models and downscaling solutions have been developed to translate global climate modeling results to finer grid resolutions. These solutions may consider more detailed information about local conditions and populations. These models are essential in providing more actionable climate data to the DoD for targeted regional challenges.[59]

Meanwhile, an increasing need to characterize the more dynamic Earth system has also led to advances in shorter-term forecasting for weather and other associated Earth systems. While extremely useful in predicting the evolution of wildfire smoke or the intensification of a tornado or a hurricane, these numerical weather prediction models are computationally intensive. Furthermore, large ensembles of such models are desirable to improve performance and characterize uncertainty, multiplying computational needs. Artificial intelligence methods, particularly deep learning, foundation models, and Physics-Informed Neural Networks (PINNS), are increasingly used by the scientific community to emulate these computationally intensive models in a fraction of the time and should be investigated further for operational applications.[60]

Some emerging solutions bridge the gap between these scales of models, including sub-seasonal to seasonal (S2S) to annual forecasts and are very promising as an avenue to provide climate information and services on actionable timescales.

For example, today, NOAA provides seasonal hurricane outlooks and El Niño forecasts. The Navy Earth System Prediction Capability (ESPC) developed at the Naval Research Laboratory (NRL) now provides 45-day atmospheric-ocean predictions, which include an ensemble mean and measure of uncertainty.[61] This model couples Navy operational components such as the Navy Global

56. IPCC, *Summary for Policymakers, In: Climate Change 2023: Synthesis Report* (Geneva, Switzerland: IPCC, 2023), 1-34, doi: 10.59327/IPCC/AR6-9789291691647.001.

57. "Exascale Performance of the Simple Cloud Resolving E3SM Atmosphere Model," E3SM, Feb. 28, 2023, https://e3sm.org/exascale-performance-of-the-simple-cloud-resolving-e3sm-atmosphere-model/.

58. "GCAM: Global Change Analysis Model," GCIMS, https://gcims.pnnl.gov/modeling/gcam-global-change-analysis-model.

59. Filippo Giorgi, "Thirty Years of Regional Climate Modeling: Where Are We and Where Are We Going next?" *JGR Atmospheres* 124, no. 11 (June 2019), https://doi.org/10.1029/2018JD030094.

60. Sara Frueh, "How AI is Shaping Weather Research and Forecasting: An Interview with Amy McGovern," National Academies, Jan. 18, 2024, https://www.nationalacademies.org/news/2024/01/how-ai-is-shaping-weather-research-and-forecasting-an-interview-with-amy-mcgovern; Amy McGovern et al., "Developing trustworthy AI for weather and climate," *Physics Today* 77, no. 1 (2024): 26–31, https://doi.org/10.1063/PT.3.5379.

61. Cassandra Eichner, "Navy Forecasting Provides 45-day Advanced Environmental Predictions," US Naval Research Laboratory, May 11, 2021, https://www.nrl.navy.mil/Media/News/Article/2602782/navy-forecasting-provides-45-day-advanced-environmental-predictions/.

Environmental Model (NAVGEM) for the atmosphere, the Hybrid Coordinate Ocean Model (HYCOM) for the ocean, and the Community Ice Code (CICE) for sea ice.[62] The Subseasonal Consortium is a group of academic, government, and non-profits that collectively aim to use sub-seasonal forecast information to improve global access to food, energy, water, and security in a changing climate.[63]

Global climate change models can be improved by using sensors or sensor networks that monitor the Earth, oceans, and space. An increasing number of Earth observations are available to characterize planetary change. Much of this effort has been led by NASA, including open-source data resources gathered under the Earth Information System (EIS) project from satellite constellations such as A-train and more targeted observation systems for specific environmental challenges, such as CarbonMapper and Plankton, Aerosol, Cloud, ocean Ecosystem (PACE).[64] Global temperature and air quality data are increasingly available, and the Argo has collected ocean surface data floats.[65] In the future, there is a need for accurate, high-resolution (meters to Km) measurements of GHG emissions and fluxes between the earth and the atmosphere. Such data is needed from low Earth orbit (LEO) constellations but ultimately will also be required from satellites with infrared spectrometers on Geostationary orbit that will provide highly accurate (99.3% or higher), persistent daily observations of GHG emissions at a few Km resolution over continental land masses.[66] Leaders and partners in this technical space include NASA, the United States Geological Survey (USGS), the National Geospatial-Intelligence Agency (NGA), the National Reconnaissance Office (NRO), and commercial satellite data sources such as GHGSat and others.

In addition to carbon monitoring from Earth and space, different satellite systems exist to provide weather data and information. The NOAA Joint Polar Satellite System (JPSS) is such a system.[67] JPSS provides global observations that contribute to short- and long-term forecasts, which help NOAA predict severe weather events. Five satellites are in the constellation, some currently flying and others scheduled to fly. Currently flying are the NOAA/NASA Suomi National Polar-orbiting Partnership satellite, NOAA-20, and NOAA-21. Upcoming satellites are JPSS-3 and JPSS-4. Because of the total global coverage these satellites provide twice a day, they provide the majority of data that inform weather forecasting in the U.S. They also offer critical observations during severe weather events.

Information produced from models or data from sensors or sensor networks is fed into planning cells for use by decision-makers. Planning cells exist in the DoD, particularly at the regional level. Examples include United States Indo-Pacific Command's (USINDOPACOM) Climate Change Impact (CCI) Program and United States Africa Command's (USAFRICOM) Strategic Risk Branch. Both entities perform functions related to observing, predicting, planning, and educating more extensively in preparation for changing climatic conditions. In many cases, these activities were not staffed by scientists (climatologists, meteorologists, oceanographers, etc.); military officers, government civilians, and contractor personnel filled a vital gap in future planning. In addition, the focus of these organizations is regional rather than DoD-wide.

62. Neil Barton et al., "The Navy's Earth System Prediction Capability: A new global coupled atmosphere-ocean-sea ice prediction system designed for daily to subseasonal forecasting," *Earth and Space Science* 8, no. 4 (Sept. 2020), https://doi.org/10.1029/2020EA001199.

63. "Subx is now the subseasonal consortium," The Subseasonal Consortium, http://weather.ou.edu/~kpegion/subc/.

64. "Earth Information System (EIS)," NASA, https://www.earthdata.nasa.gov/eis.

65. "What is Argo?" UC San Diego, https://argo.ucsd.edu/.

66. "The Geostationary Carbo Cycle Observatory," The University of Oklahoma, https://www.ou.edu/geocarb.

67. "Joint Polar Satellite System," NOAA National Environmental Satellite, Data, and Information Service, https://www.nesdis.noaa.gov/our-satellites/currently-flying/joint-polar-satellite-system.

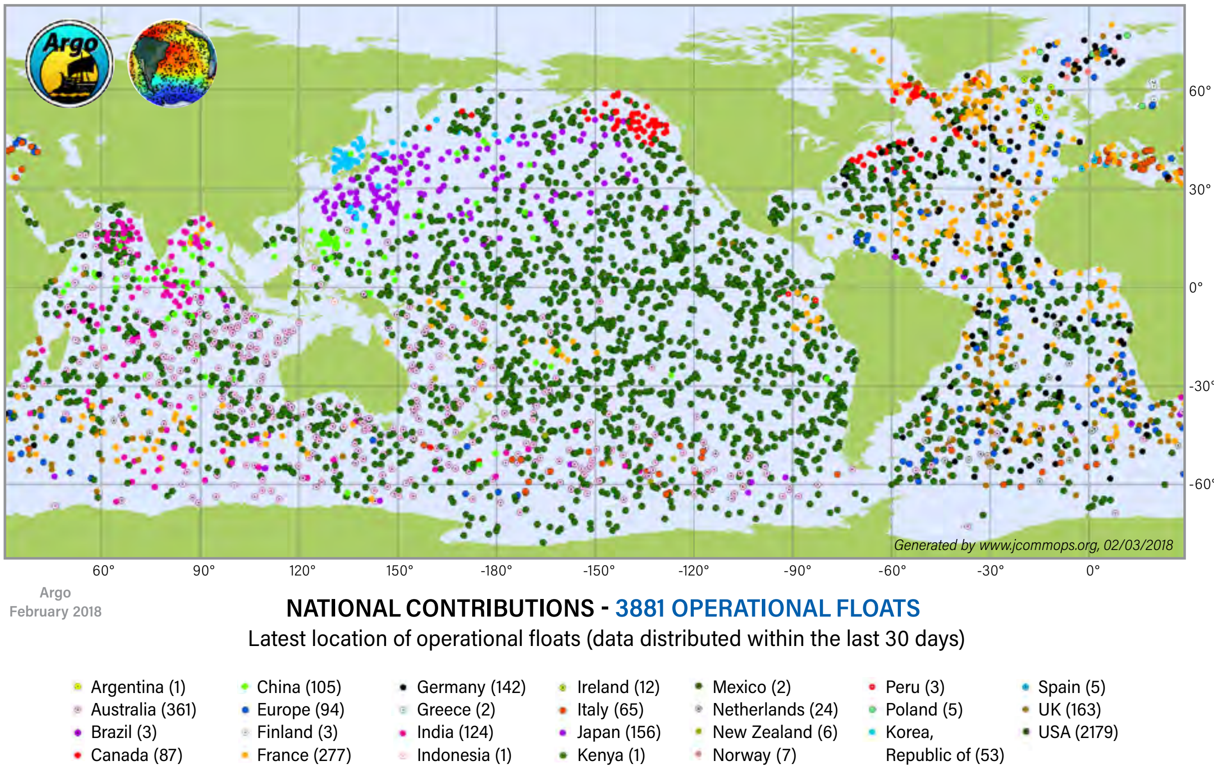

Figure 19. The ARGO Float System.[68]

Figure 20: Geostationary Carbon Cycle Observatory.[69]

68. Figure 19 Source: Wikimedia Commons.

69. Figure 20 Source: Dr. Berrien Moore III, Weather and the Planetary State in a Changing Climate Briefing to the DSB, May 10, 2023.

Major Gaps and Challenges

Climate change is driven by a massively interconnected and complex system. While helpful, climate forecasts are uncertain and should be used cautiously on short-term and regional scales. Uncertainty is driven by challenges, including predicting societal response to climate, incomplete greenhouse gas characterization, under-observed Earth regions, and complex dynamics such as climate tipping points. Anticipating amplified extreme weather events in a climate-changed world will further strain current Earth systems data, modeling, and computational capability.

While the global climate and weather scientific communities continue to push the science of prediction further, several gaps already impact the planning ability of the DoD and intelligence community.

These include:

- Climate decision support: Current climate modeling results are not easily accessible to planners, limiting their application to defense. With centralization and standardization, the abundance of climate models, predictions, and standards can add further clarity and communication about critical climate risks.
- Under-observed Earth systems: A lack of data has left significant gaps in climate modeling capability in DoD-relevant Earth systems, including atmospheric/aerosol interactions and deep ocean dynamics. While on-site and remote sensors exist to monitor climate change, more global sensor network data must be collected. Agencies such as the Office of Naval Research (ONR), Defense Advanced Research Projects Agency (DARPA), NGA, NASA, and NOAA each provide such data, though a single office within the DoD needs to be included to consolidate the data. In addition, shortfalls exist in global undersea sensing networks for persistent fusion of atmosphere, ocean, Earth, and cryosphere information data. These gaps limit the ability to predict climate change impacts on operational systems and limit important secondary climate predictions, including the variability of El Niño, climate tipping points, and precipitation distribution.
- Risk Assessment: Many existing extreme weather forecasts and risk models rely on historical data and do not consider current or future climate change. This limits the ability of planners to prioritize disaster mitigation efforts, from coastal defense to prepositioning of assets. While climate-informed and seasonal risk forecasts are emerging using traditional and artificial intelligence methods, they require further investigation and must be tailored to domains of interest.

As noted above, climate change planning cells exist. However, they are regionally focused rather than centrally focused. Moreover, these regional cells only sometimes integrate with non-DoD agencies, such as NOAA, NASA, DOE, and the Intelligence Community, and are generally staffed by non-scientific military or government personnel. The DoD has formulated a Directive assigning roles and responsibilities concerning climate change, DoD Directive 4715.21, "Climate Change Adaptation and Resilience." The DSB believes that an opportunity exists to form a more centralized DoD Climate Planning Cell that would collect inputs from climate models and sensing data and assimilate that information for decision-makers at the DoD-wide level and the CCMDs. Such a centralized entity would also ensure planning assumptions remain current even at the regional level.

In addition, Chairman of the Joint Chiefs of Staff (CJCS) Instruction 3810.01F (2019) indicates that the U.S. Air Force is responsible for "climate monitoring and analysis and prediction capabilities for all elements of the DoD."[70] Such an instruction implies that the U.S. Air Force would be the authoritative, single source for climate-related information for the DoD. The DSB learned that the Department of Air Force Weather Climate Support (14th Weather Squadron) is the designated authoritative source for DoD climate data. However, the Squadron is not adequately resourced to carry out the mission at scale.

Findings and Recommendations

Finding 1

Climate modeling efforts and data sets exist. However, these are insufficient, not tailored to defense systems, not accurately downscaled to regions or time scales of interest, and do not incorporate classified data sets.

Recommendation 1.1

[DepSecDef, CCMDs, Assistant Secretary of Defense for Energy, Installations, and Environment (ASD(EI&E))] Create a DoD Climate Planning Cell to generate and integrate climate data and decision-support tools to guide climate-informed policy, strategy, and mission planning, including assessment of climate change impacts on adversaries. Implement immediately (0-1 year).

Recommendations 1.2

[DoD Climate Planning Cell] Working with Air Force Weather Squadron, Navy, DARPA, NGA, NASA, NOAA, consolidate and collect more global sensor network data, including creating a global undersea sensing network, for persistent fusion of atmosphere, ocean (surface and subsurface), terrestrial, and cryosphere information data. Near term (0-2 years).

Recommendations 1.3

[ASD(EI&E), Under Secretary of Defense for Research and Engineering (USD(R&E))] Continue to work with DOE, the interagency and other experts, and the IC to leverage exascale and other computing methods for development of future global and regional scale climate models accurate at DoD-relevant operational time scales of one to ten years. Near term (0-2 years).

Recommendation 1.4

[DoD Climate Planning Cell, USD(R&E)] Working with ASD(EI&E), Air Force, Navy, the Joint Staff, and others, inform NOAA, NASA, and DOE of key CCMD requirements and couple Global Climate Models (GCM) downscaled to relevant regions with advanced sub-seasonal to seasonal weather prediction tools for future DoD operations planning. Medium term (3-5 years).

70. Bill Danyluk, "DoD Operational Climatology and Vision," (USAF 14th Weather Squadron Presentation to DSB, Strategic Analysis Inc. Executive Conference Center, Arlington, VA, March 21, 2023).

Climate Models and Sensor Example Solutions

Below, we describe recent and current efforts demonstrating a path forward for these recommendations and suggest potential partners for execution.

Among the most notable coordinating activities are the Strategic Environmental Research and Development Program (SERDP) and the Environmental Security Technology Certification Program (ESTCP), DoD environmental, resilience, and installation energy and water research programs. SERDP and ESTCP have established relationships across the Services, academia, and other Federal Agencies, allowing them to oversee activities from basic and applied research to demonstration to validation.

DARPA has had several efforts to address gaps in climate modeling and data. This includes AI-assisted Climate Tipping-point Modeling (ACTM), which explored AI-assisted modeling of complex climate-related processes.[71] Additional DARPA efforts to enable decision-making, such as World Modelers, have sought to provide fundamental tools for modeling complex and interdependent challenges like climate and food security.[72] DARPA also explored larger-scale ocean sensor systems on Ocean of Things and targeted environmental sensing, including a velocity sound profiler.

Several Minerva Research Initiative projects have explored the relationship between climate and social science, mainly focusing on impacts on sociopolitical stability. Better connections are needed between these social science studies and the needs of combatants, which is part of the goal of the Providing Research and End User Products to Accelerate Readiness & Environmental Security (PREPARES) program, funded by the Office of the Secretary of Defense for Research and Engineering. The Central Intelligence Agency (CIA) Political Instability Task Force assesses the impact of various governmental and societal issues on global geopolitical instability but has not yet coupled the effects of climate change to such assessments.[73]

ONR has had several programs on Arctic situational awareness and coastal resilience. These include the Arctic Mobile Observing System (AMOS), which enables improved Arctic communications, navigation, and autonomy. Through their partnership with the National Oceanographic Partnership Program (NOPP), the NOPP Hurricane Coastal Impacts (NHCI) project has targeted hurricane threats, developing new sensing and forecasting tools to enable greater coastal resilience.[74]

A recent Center for Naval Analyses (CNA) study examined how climate change can affect Navy platforms, sensors, and weapon systems. The study determined the major atmospheric and oceanic climate drivers, mapped the drivers to a representative set of Navy platforms and systems they will affect, and then used vignettes to investigate the physical linkages between climate drivers and military systems. The study yields an understanding of the physical mechanisms through which environmental changes can affect naval platforms and systems.[75]

71. Erica Briscoe, "AI-assisted Climate Tipping-point Modeling (ACTM)," DARPA, https://www.darpa.mil/program/ai-assisted-climate-tipping-point-modeling.

72. Erica Briscoe, "World Modelers," DARPA, https://www.darpa.mil/program/world-modelers.

73. "Socio-Political Drivers of Instability: Lessons Learned from the Political Instability Task Force," (Presentation to DSB, Strategic Analysis Inc. Executive Conference Center, Arlington, VA, June 22, 2023).

74. "NOPP Hurricane Coastal Impacts," NOPP, https://nopphurricane.sofarocean.com/.

75. R. Filadelfo, A. Ilachinski and S. Starcovic (2023). *Climate Change Implications for Navy Operations, Platforms, and Systems: Setting a Research Agenda.*

The Army Corps of Engineers has led the charge on Engineering with Nature, a community of researchers and projects that align natural and engineering processes, often resulting in increased climate resilience.[76]

Several tools targeting specific DoD climate preparedness needs are now available through the DoD Climate Resilience Portal.[77] This includes the DCAT, which assesses long-term climate change exposures for military bases and assets. The U.S. Air Force Climate (14th Weather Squadron) and U.S. Naval Meteorology and Oceanography Commands provide data sets and models for climate intelligence, anomaly detection, and early warning systems.

Recently, MethaneSAT was launched, detaching from the SpaceX Transporter-10 rocket.[78] This satellite, developed by a non-profit Environmental Defense Fund subsidiary, will detect and quantify total methane emissions over wider areas than possible using other satellites. Data from the satellite will enable regulators and companies to track methane emissions.

Many more examples stand out in the civilian research community. Government agencies organized long-standing climate observation, data assimilation, and modeling efforts, including NASA's EIS, NOAA's National Centers for Environmental Information (NCEI), and DOE's climate modeling capabilities, such as E3SM. Industry also provides more climate resources than ever, including satellite companies like Planet Labs and Maxar Technologies. Expanded partnerships with these agencies and industries have the potential to accelerate DoD climate modeling capabilities and climate preparedness significantly.

Climate Planning Cell Example Solutions

The DSB recommends the establishment of a DoD Climate Planning Cell because of its potential utility in assimilating model outputs and sensor data, quantifying uncertainties, and interfacing with non-DoD agencies, which could enhance the DoD's climate knowledge. Such information would be helpful to DoD decision-makers working in the areas of infrastructure planning and risk management, the development of mitigation strategies, the provision of planning tools for CCMDs, and the development of acquisition requirements. The Board recommends integrating the tasks of these various activities with more considerable efforts within the various agencies of the U.S. Government. This Climate Planning Cell would not replace extant activities but would support and supplement their work.

The figure on the following page illustrates the advantages of such a Climate Planning Cell.

76. "About EWN," Engineering With Nature, https://ewn.erdc.dren.mil/about/.

77. DOD Climate Resilience Portal, https://www.climate.mil/.

78. Sharmila Kuthunur, "SpaceX rocket launches pioneering methane-tracking satellite to orbit," Space.com, March 5, 2024, https://www.space.com/methane-tracking-satellite-launch-spacex-transporter-10.

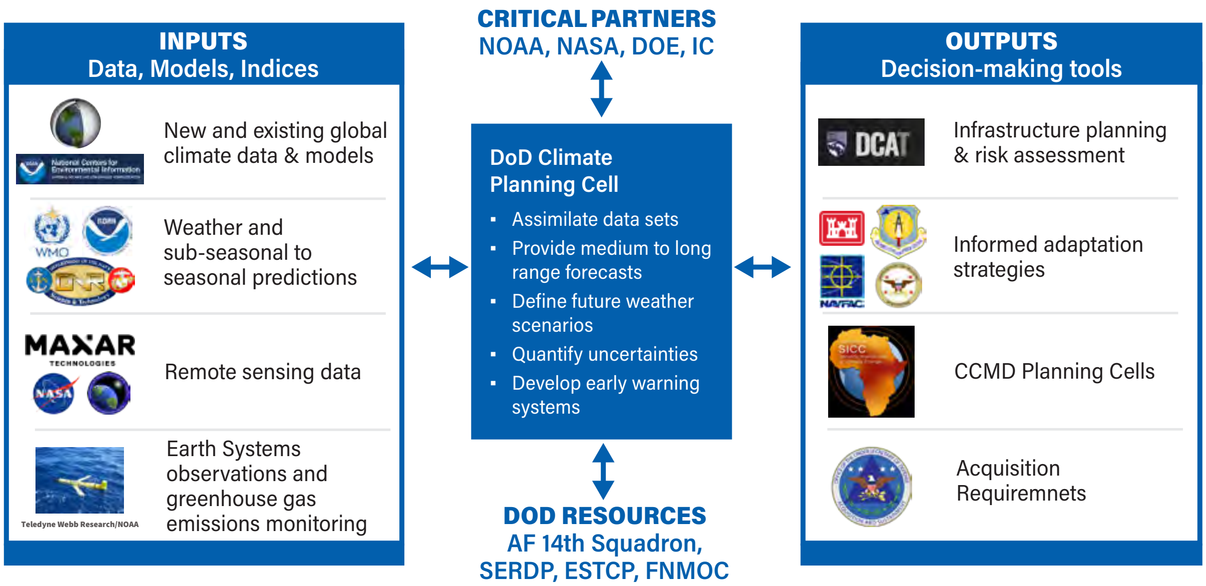

Figure 21. Potential Climate Planning Cell structure.

The mission of such a cell should include:

- Integrating Climate Data from across the United States Government (USG). The Climate Planning Cell would fuse data—both unclassified and classified—from the sea floor to space to create a Common Climate Operating Picture.
- Evaluating the efficacy of climate models used by the Services, Defense Agencies and Activities, and Combatant Commanders. The Climate Planning Cell will ensure that the same global model(s) are used across the breadth of the U.S. government. Where smaller scale models are required (e.g., geographic combatant commander, remote basing), the Climate Planning Cell will maintain the visibility of such models to ensure consistency and efficiency.
- Liaising with Armed Services, Defense Agencies and Activities, and Combatant Commanders to provide the best planning guidance based on current science. Issue Climate Planning Guidance to support these activities, including probabilistic conditions and variations for future wargames.
- Providing recommendations for areas of study for national security professionals based on predicted conditions in geographic areas and specific physical domains (e.g., sea, air, space).

The functions and tasks of the Climate Planning Cell should be to:

- Integrate Climate Data from across the USG. To integrate data from across the USG, the Climate Planning Cell:
  - Serves as the Secretary of Defense's executive agent on matters relating to climatological change prediction.
  - Provides a Climate Common Operating Picture that fuses classified and unclassified data from across various USG entities (and select Allies (e.g., FVEY)) from sea floor to space to better understand gaps and seams in domains, geographic areas, and data sources as well as identifying interactions that could produce a security opportunity or create a security challenge

associated with changing climate conditions. NASA's Global Modeling and Assimilation Office (GMAO) focuses on effectively combining Earth system data sets and would serve as an ideal partner and exemplar for such an operating picture. The NOAA National Centers for Environmental Information contains an extensive archive of environmental data that can be leveraged to explore trends. At the same time, the NASA Earth Information System combines extensive satellite observations with corresponding data tools and models to enable a better understanding of Earth systems.

- Coordinates with weather activities within DoD (e.g., Air Force 14th Weather Squadron, Navy Fleet Numerical Meteorology and Oceanography Center) to provide data usable to other government agencies, entities, and selected Allies.
- Evaluate the efficacy of climate models used by the Services, Defense Agencies and Activities, and Combatant Commanders. To carry out this function, the Climate Planning Cell:
  - Provides expert guidance on the GCM used by DoD.
  - Provides expert guidance of regional and local models to ensure consistency and data provenance. In addition to increasing resolution, the Board recommends exploring regional models that consider socioeconomic drivers and connect these models to defense and regional impacts. Explorations such as those performed by Minerva and PREPARES will enable improved preparation for potential climate-induced instability, migration, and conflict.

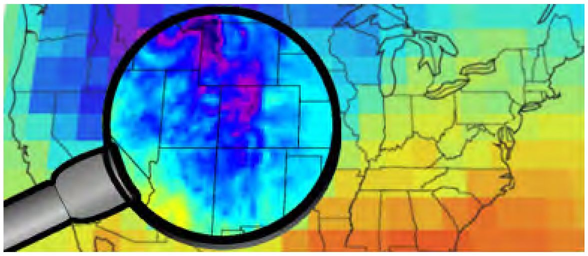

Figure 22. Climate downscaling.[79]

  - Examines technological advances to further understanding of climate. For example, the DOE labs introduced exascale computing to dramatically increase the resolution of climate models down to the scale of a few kilometers.[80] This effort would consider substantial differences in rainfall, temperature, and natural hazard risk that arise due to topographical conditions, particularly near mountains and along coastlines. Working with these models will enable better prediction for site-specific climate impacts, such as those for a military base or port. Partnering with the DOE to target regions of DoD interest and leveraging these higher-resolution models could enable better predictions in tools like DCAT.
  - Coordinates with stakeholders in the various departments, agencies, activities, research institutions, and FFRDCs to advance modeling and simulation, especially in the 1 to 10- year planning and execution horizon. Tools like NOAA's seasonal hurricane and El Niño forecasts show how targeted data collection can enable longer-term predictions, and AI-driven seasonal wildfire forecasts are under investigation. The Navy ESPC has extended its forecast window to 45 days. Fundamental investments are still needed to bridge the gap between climate and weather models at scales to inform operational plans.

79. Figure 22 Source: NOAA Geophysical Fluid Dynamics Laboratory.

80. Bader, "Lawrence Livermore National Laboratory: Climate Modeling for Climate Change Prediction."

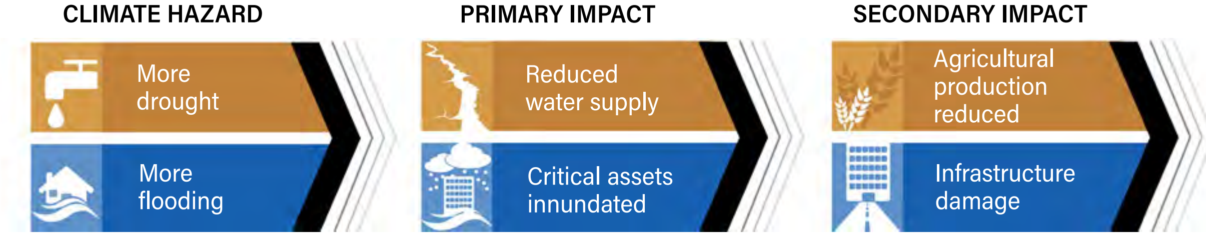

Figure 23. Climate change impacts workflow.[81]

- Provides, on a yearly basis, guidance for the Departments, Agencies, and Activities based on USG modeling efforts. This Climate Planning Guidance will focus on the 1-10 year planning and execution horizon (2 Future Years Defense Program (FYDP)) and identify climate trends and trajectories in the 2-4 FYDP period (10-20 years). The guidance would be provided to:
  - The various intelligence agencies for impact analysis on other regions and nations.
  - The various acquisition agencies for impact analysis and specification adjustment for present and future purchases.
  - The Services and Combatant Commanders to provide probabilistic climate conditions and potential variations for use in Operation Plans (OPLAN) and Title 10 wargaming activities. The Climate Planning Cell can take advantage of wargames already conducted by USAFRICOM (Security Implications of Climate Change) and USINDOPACOM Center For Excellence in Disaster Management and Humanitarian Assistance (CFE-DM) as a baseline.
  - The Services, Defense Agencies and Activities, and Combatant Commanders to assist in their defense and contingency planning (along with classified intelligence assessments).
- Serves as a central repository to assist the Services, Defense Agencies, and Combatant Commanders in interpreting climate data and potential impacts on future operations.
- Partners with non-traditional groups that have interests and equities in hazard prediction. While traditional risk modeling relies on historical averages, an increasing number of insurance and real estate companies are using climate predictions for risk assessment; however, most of these algorithms are proprietary. The Federal Emergency Management Agency's (FEMA) Hazus model incorporates infrastructure and calculates damage from natural and simulated disasters. However, this does not include international or DoD assets, nor does it consider the mission impacts of potential disasters. By combining resources, the Planning Cell could leverage and fuse existing external source data to provide more comprehensive risk assessments to DoD facilities and surrounding areas.
- Provides recommendations for areas of study for national security professionals based on predicted conditions in geographic areas and specific physical domains (e.g., sea, air, space). To provide areas of study, the Planning Cell should:
  - Identify learning areas and objectives based on what leaders anticipate at operational and strategic levels of war.

81. Figure 23 Source: Department of Defense.

- Recommend curricula content based on climate trends and trajectories, as well as predicted outcomes of such trends.

Climate Education and Training

State of the Science

Risk analysis is essential for DoD's response to climate change. Such assessments identify and evaluate risks and articulate strategies for mitigating and managing risks. Two seminal documents have been produced in response to Executive Order (EO) 14008, which requires the Secretary of Defense to develop "an analysis of the security implications of climate change (Climate Risk Analysis) that can be incorporated into modeling, simulation, war-gaming, and other analyses."[82] Foremost, the DoD Climate Change Adaptation Plan "provides a roadmap to ensure the department maintains the ability to operate under changing climate conditions while preserving operational capability and protecting systems essential to our success."[83]

In October 2021, the Department of Defense published the DoD Climate Risk Analysis.[84] The document describes how it plans to adapt and address climate change. The DoD Climate Risk Analysis contains six sections whose descriptions are paraphrased below from the document's Executive Summary.[85]

- Section I describes "key security implications of climate change to DoD, including DoD's role supporting whole-of-government and international efforts in concert with allies and partners."
- Section II reviews the department's "climate policy and responsibilities," including citing key documents.
- Section III "presents a review of climate hazards, risks, and security implications."
- Section IV describes how "DoD will incorporate consideration of climate into relevant strategy, planning, and processes."
- Section V describes "interagency scientific and intelligence products and experts, which could support future analyses of climate risk" and provides "funding for exercises, wargames, analyses, and studies related to climate change."
- Section VI is the document's conclusion, describing how it provides "an initial review of the security implications of climate change" for DoD and where other guidance will be found (as of 2021).

Two appendices round out the document. The first lists all the climate-related statutes, DoD

82. Executive Office of the President, *Tackling the Climate Crisis at Home and Abroad,* Executive Order 14008 (2021), 7621, https://www.federalregister.gov/documents/2021/02/01/2021-02177/tackling-the-climate-crisis-at-home-and-abroad.

83. Department of Defense, Office of the Undersecretary of Defense (Acquisition and Sustainment), 2021, *Highlights and Examples for the Department of Defense Climate Adaptation Plan*, 1, https://media.defense.gov/2021/Nov/03/2002886171/-1/-1/0/HIGHLIGHTS-AND-EXAMPLES-FOR-DOD-CLIMATE-ADAPTATION-PLAN.PDF.

84. Department of Defense, Office of the Undersecretary for Policy (Strategy, Plans, and Capabilities), 2021, *Department of Defense Climate Risk Analysis*, Report Submitted to National Security Council, https://media.defense.gov/2021/Oct/21/2002877353/-1/-1/0/DOD-CLIMATE-RISK-ANALYSIS-FINAL.PDF.

85. *Department of Defense Climate Risk Analysis*, 2.

issuances, policies and guidance, and executive orders. The second appendix provides examples of tools, funds, and programs that describe how DoD will work on climate-related issues and considerations with partners.

In March 2021, the Secretary of Defense directed the establishment of the Department of Defense Climate Working Group to coordinate the Department's responses to EO 14008 and subsequent climate change directives and track implementation of progress against future climate goals. In 2022, the Deputy Secretary of Defense established a Climate Literacy sub-working group.[86] This group reports to the DoD Climate Working Group and the Chief Sustainability Officer. This group aims to help integrate climate change factors into DoD's education and training programs. In 2022, the sub-working group achieved a key milestone by defining climate literacy. The definition is "understanding how the climate impacts DoD missions, how DoD operations impact the climate, and how to make climate-informed decisions."[87] Climate literacy has been identified as a workforce development priority for the Department.

Major Gaps and Challenges

As noted above, the Department of Defense Climate Risk Analysis and Climate Adaptation Plan are the key sources of information about the DoD's plans to adapt and address climate change. However, the Climate Risk Analysis has not been updated since 2021. The DoD has taken a long list of actions to address climate change since 2021. These actions run the gamut of improving the resiliency of installations, understanding the threat that climate change can pose to military forces, educating the force on that threat, protecting warfighters, potential ramifications of new and more frequent access to locations critical to military operations, and fighting in an increasingly complex environment because of climate change. These developments could be part of an updated risk analysis. The original core document also cited the need for a whole government response and coordination with Allies and partners to respond to risks associated with climate change. A single document containing this information could help other agencies and countries understand the DoD's most updated view of the risks of climate change. Outdated planning assumptions could prove equally problematic to agency leaders, Allies and partners, and operational commands.

In addition, the rate of changes in the Earth's system appears to be occurring more quickly than in the past. The figure below shows the trends of the Earth's system in recent decades.[88]

The increase in the rate of change points to a need for more frequent updates to the DoD Climate Risk Analysis, which, for many audiences, serves as the Department's core guidance on this matter.

The actions described previously in this section by the DoD regarding climate literacy are not far-reaching. Most audiences for such literacy efforts appear to be at the policy level and senior decision-makers. Only some strategic planners and operational support personnel have yet to receive structured insights about the impacts of climate change.

86. "DOD, Other Agencies Release Climate Adaptation Progress Reports," US Department of Defense, October 6, 2022, https://www.defense.gov/News/News-Stories/Article/Article/3182522/dod-other-agencies-release-climate-adaptation-progress-reports/.

87. Department of Defense, Office of the Undersecretary of Defense (Acquisition and Sustainment), 2022, *Department of Defense Climate Adaptation Plan 2022 Progress Report*, Report Submitted to National Climate Task Force and Federal Chief Sustainability Officer, 4 October 2022, 5, https://media.defense.gov/2022/Oct/06/2003092213/-1/-1/0/2022-DOD-CAP-PROGRESS-REPORT.PDF.

88. Will Steffen et al., "The Trajectory of the Anthropocene: The Great Acceleration," *The Anthropocene Review* 2, no. 1 (Jan. 2015), https://doi.org/10.1177/2053019614564785.

EARTH SYSTEM TRENDS

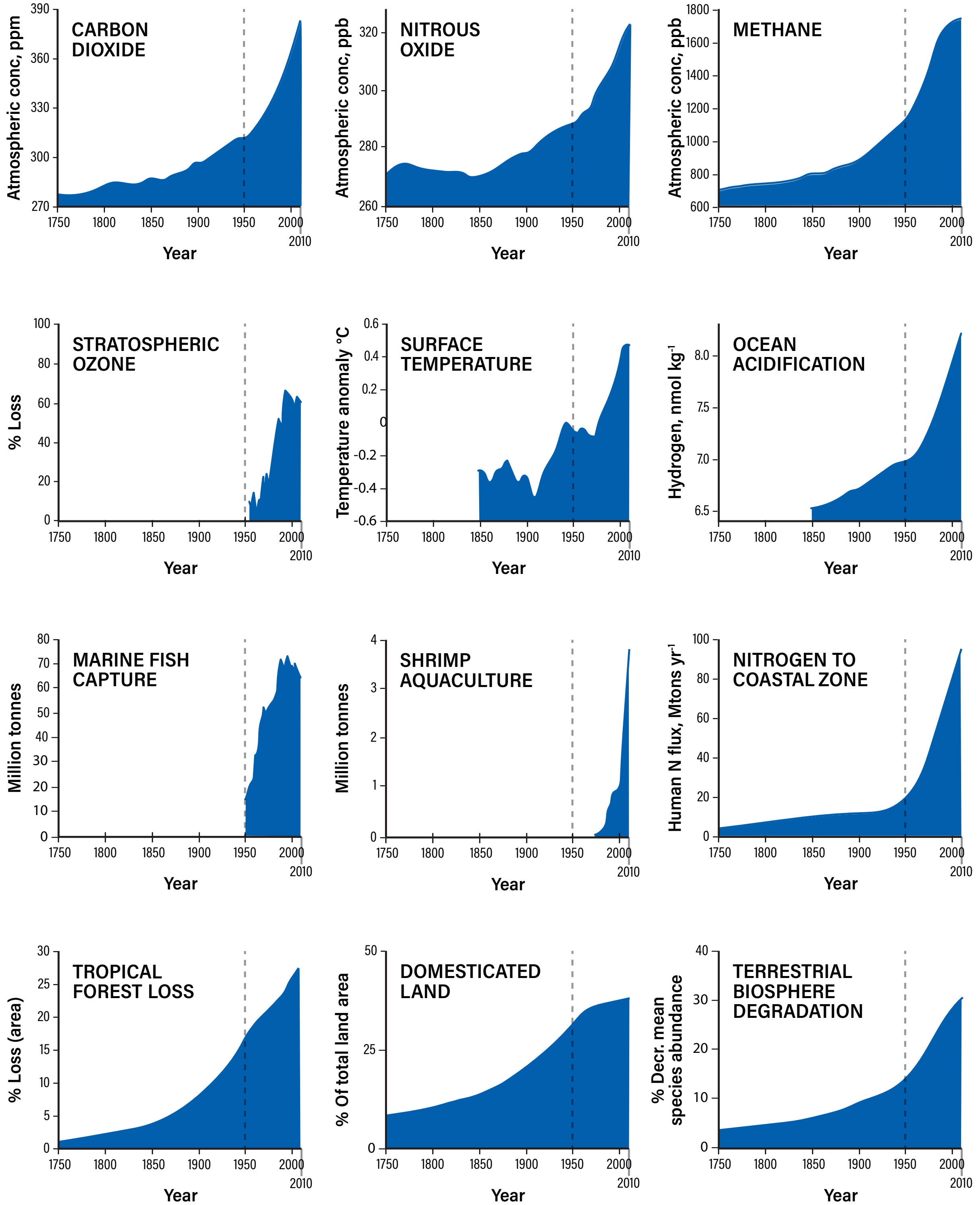

Figure 24. Earth system trends.[89]

89. Figure 24 Source: Steffen et al., *The Anthropocene Review*.

In addition, the degree to which climate change is integrated into professional military education is found to be wanting.[90] Pollock and Ellis note that climate change remains "underrepresented in national security curricula."[91] The authors also note that teaching a single course targeted at climate security issues is "necessary but not sufficient."[92]

Combatant Commands have, to varying degrees, provided exposure to their forces to climate change issues and their impacts on military missions. For example, INDOPACOM's CFE-DM works to bridge the gap in understanding between civilian and military organizations during disaster relief operations.[93] It facilitates the education and training of U.S. and partner nations in civil-military operations. Naturally, training and education about humanitarian response and the military's role in crises help with literacy about such operations. Inserting climate change subtexts into wargames and introducing climate change mitigation measures in security cooperation options are in-stride opportunities to increase climate literacy. INDOPACOM's CCI program also provides education on climate change effects and impacts on military operations in the theater. Among CCI's many benefits, it provides data to inform better how climate change impacts a population's security needs.[94]

Findings and Recommendations

Finding 2

There is a need for enhanced operational climate education and training across the Services.

Recommendation 2.1

[Under Secretary of Defense for Policy (USD(P))] Triennially revisit and update DoD's Climate Risk Analysis. Develop guidance and policies for CCMDs and military operational planners to respond to these evolving realities. Immediate implementation (0-1 year).

Recommendation 2.2

[Office of the Under Secretary of Defense for Personnel and Readiness/Deputy Assistant Secretary of Defense for Force Education and Training (OUSD(P&R)/DASD (FE&T)), Joint Staff J7, Services] Enhance climate literacy for strategic planners and operational support personnel, integrate climate considerations, planning tools, and scenarios into operational command courses, Services' Advanced Warfighting School, and courses designed for staff headquarters and align climate planning with Allies. Near term (0-2 years).

90. Greg Pollock and John C. Ellis, "Integrating Climate Change into Professional Military Education," *Journal of Security, Intelligence, and Resilience Education* 12, no. 5 (2021), https://jsire.org/integrating-climate-change-into-professional-military-education/.

91. Pollock and Ellis, "Integrating Climate Change into Professional Military Education," 1.

92. Pollock and Ellis, "Integrating Climate Change into Professional Military Education," 1.

93. Joe Martin, "CFE DM: Command Brief" (Presentation to DSB, SA Inc. Executive Conference Center, Arlington, VA, May 10, 2023).

94. Joseph Green et al., *2050 Indo-Pacific Climate Change Impact Analysis*, (Pacific Disaster Center: 2023), https://www.cfe-dmha.org/climate-change-impacts.

Climate Education and Training Example Solutions

CFE-DM and CCI serve as excellent examples of enhancing climate literacy. Other theaters are engaged in related activities. For instance, USAFRICOM includes workforce education as part of its Operations, Activities, and Investments when it considers the strategic context of climate change.[95]

Recently, the Office of the Assistant Secretary of Defense for Readiness and National Defense University launched a workshop series for faculty across the Service academies, war colleges, and command and staff schools designed to address the operational environment U.S. military forces are likely to face. Climate change's impact on the military's operational mission is part of the series. Preparing military educators to be able to prepare military leaders to adapt and respond to climate change is a crucial aspect of the initiative. Military leaders equipped to make climate-informed decisions are an anticipated outcome.[96] Developments such as this are a good step toward enhancing climate literacy throughout the Department.

Climate Intervention Sensing

State of the Science

Climate intervention has been proposed as an alternative or complementary capability to mitigation and adaptation strategies to address climate change. Proposed methods for climate intervention, which generally aim to modify the Earth's albedo, include changing the reflectance and emission properties of land, ocean surface, and the Earth's atmosphere to alter the global radiative energy balance.

The average solar energy impacting Earth is approximately 340 W/m^2, with approximately 30% of this energy reflected into space by clouds, atmospheric particles, and land and ocean surfaces. Thus, approximately 70% of the incident solar radiation heats the Earth through atmospheric and surface absorption. Climate intervention aims to increase the energy reflected and emitted, thus reducing the energy absorbed by the Earth. A global increase in reflectance or emission of approximately 1 W/m^2 is necessary to offset the observed global temperature rise.

The National Academies of Sciences, Engineering, and Medicine has conducted two studies on Solar Geoengineering, which is the term they adopted to address approaches used to modify the solar energy reflected into space. Currently, two promising and controversial approaches for climate intervention are Stratospheric Aerosol Injection (SAI) and Marine Cloud Brightening (MCB).[97] As illustrated in Figure 25, SAI involves the introduction of aerosols and particulates into the stratosphere to increase the reflectance of incident radiation through increased light scattering. MCB is an alternative approach for increasing the brightness of marine clouds through particulate injection, which leads to increased water droplet size and density in the clouds. A third approach called Cirrus Cloud Thinning (CCT) addresses techniques for reducing the impact of cirrus clouds in preventing surface emissions from

95. Chris McCook, "USAFRICOM Strategic Risk Branch (J563): Security Implications of Climate Change," (Presentation to DSB, SA Inc. Executive Conference Center, Arlington, VA, July 19, 2023).

96. Joseph Clark, "Military Educators Converge on New Workshop Series to Discuss Resilience in Evolving Climate, Security Environment," Department of Defense, Sept. 26, 2023, https://www.defense.gov/News/News-Stories/Article/Article/3539024/military-educators-converge-on-new-workshop-series-to-discuss-resilience-in-evo/.

97. National Research Council, *Climate Intervention: Reflecting Sunlight to Cool Earth*, (Washington, DC: The National Academies Press, 2015), https://doi.org/10.17226/18988; National Academies of Sciences, Engineering, and Medicine, *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance*, (Washington, DC: The National Academies Press, 2021), https://doi.org/10.17226/25762.

escaping to space. Little investigation of CCT has been conducted and will not be addressed further in this report.

The basis for MCB is observed using space-based Electro-Optical and Infrared (EO/IR) sensors, which readily capture surface shipping tracking in brightness patterns of maritime clouds, as seen in Figure 26. Particulates emitted from the ship propulsion system rise in the atmosphere and interact with water vapor, serving as nucleation sites to increase water droplet size and density in maritime clouds. To be effective in modifying the global radiative balance, MCB would need to be deployed at a global scale.

The basis for SAI providing a cooling effect is known from the study of volcano eruptions. For example, the 1991 eruption of Mount Pinatubo and its injection of sulfur dioxide (SO_2) into the stratosphere resulted in approximately 30 million tons of sulfuric acid (H_2SO_4), resulting in a measured 0.3°C cooling of the earth for approximately three years.[99] In this case, SO_2 and hydrogen sulfide (H_2S) react with O_2 to H_2SO_4, which leads to the formation of sulfate aerosols.

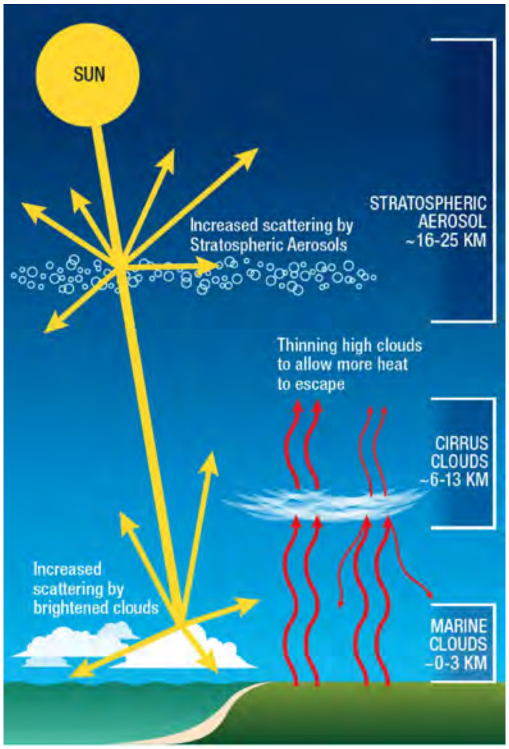

Figure 25. Solar geoengineering approaches.[98]

One concern with using sulfates is the potential degradation of the stratospheric ozone layer, which protects from harmful ultraviolet radiation. Other aerosols and particulates have been proposed for SAI, including titanium dioxide (TO_2), Alumina (Al_2O_3), silica (SiO_2), and silicon carbide (SiC). These particles mitigate ozone depletion concerns and possess a higher refractive index compared to sulfates, which would reduce the amount of needed injectant. Pope et al. estimate that the use of TO_2 would result in a 2/3rd reduction in needed

Figure 26. Ship tracks observed in the Northern Atlantic Ocean taken with the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Aqua Satellite.[100]

98. Figure 25 Source: *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance* (2021), National Academies Press.

99. National Research Council, *Climate Intervention: Reflecting Sunlight to Cool Earth*.

100. Figure 26. Ship tracks observed in the Northern Atlantic Ocean taken with the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Aqua satellite. Source: NASA image by Jeff Schmaltz.

stratospheric injectant compared to H_2SO_4.[101]

Theorists and military planners have raised a concern about the possibility of rogue actors unilaterally deploying SAI. Smith and Henly refute this argument, estimating that an effective SAI system capable of reducing the earth's temperature to 1°C would require injection of approximately 5 million metric tons of aerosols annually, which is estimated to require a fleet of 150 aircraft and an annual budget of roughly $18 billion.[102] Given the magnitude of this deployment, it is widely accepted that the deployment could not be covert with the impact widely observable by existing sensing systems. Further, even a well-funded military would see readiness degradation if called to do this work.

While large-scale deployment of SAI is observable, many have called for research to be conducted into SAI to facilitate informed policy debates.[103] In particular, The White House Office of Science and Technology Policy (OSTP) states, "Outdoor experiments would be valuable in combination with model and laboratory studies for understanding processes involved with potential SRM (Solar Radiation Modification) deployment."[104] A report by the National Academies of Sciences, Engineering, and Medicine proposes a small-scale research, typically smaller than 100X, that would result in an observable impact on climate and be conducted under an international regime of governance founded on transparency.[105]

While international collaboration in SAI research could be beneficial in creating sound policy decisions regarding issues associated with climate intervention, one must also address the concern of state actors who may conduct this type of research without transparency and then may leverage knowledge gained to produce a unilateral breakout capability.

Major Gaps and Challenges

While today's global monitoring of atmospheric aerosols and particulates will provide the capability for detecting large-scale SAI deployment, it does not produce sufficient measurement resolution to enable detection and attribution of experimentation with SAI technologies. Given this type of experimentation may be a precursor to a breakout capability for deployment and given that the stratospheric injectants may have important and unknown impacts on the atmosphere, local climate, and other military capabilities such as sensing and aircraft engine wear, it is important for the DoD to engage in persistent monitoring of atmospheric aerosols and particulates.

A program to measure stratospheric aerosols and particulates is also needed to improve atmospheric modeling and prevent strategic surprise. This program should provide a capability for the widespread measurement of atmospheric aerosols and particulates to ensure that an adversary cannot be positioned for strategic surprise in executing unilateral climate interaction action. Further,

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101. Francis D. Pope et al., "Stratospheric aerosol particles and solar-radiation management," *Nature Climate Change* 2, no. 10 (October 2012): 713-719, https://doi.org/10.1038/NCLIMATE1528.

102. Wake Smith and Claire Henly, "Updated and outdated reservations about research into stratospheric aerosol injection," *Climate Change* 164, no. 39 (February 2021): 3, https://link.springer.com/article/10.1007/s10584-021-03017-z.

103. National Academies of Sciences, Engineering, and Medicine, *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance*; *Congressional Mandated Research Plan and an Initial Research Governance Framework Related to Solar Radiation Modification*, (Washington, DC: Office of Science and Technology Policy, 2023), https://www.whitehouse.gov/wp-content/uploads/2023/06/Congressionally-Mandated-Report-on-Solar-Radiation-Modification.pdf.

104. *Congressional Mandated Research Plan and an Initial Research Governance Framework Related to Solar Radiation Modification*, 6.

105. National Academies of Sciences, Engineering, and Medicine, *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance*.

possessing the capability to deny that stratospheric tampering occurred is a valuable message to counteract potential histrionics used in psychological operations.

There is also a need for a deployable multi-purpose stratospheric aerosol and particulate sensing suite capable of deployment with forward-deployed units. This sensing suite should leverage existing and evolving sensing technologies such as those being flown in the Stratospheric Aerosol processes, Budget and Radiative Effects (SABRE) experiments. DARPA or the Strategic Capabilities Office (SCO) could pursue affordable miniaturization and hardening of measurement techniques to enable robust measurement suites at scale in forward deployed locations, such as on aircraft, naval platforms, and forward bases. This measurement data should be used to inform local models of the atmospheric aerosols and particulates and combined with global and campaign data collections to improve the Earth's radiation balance modeling.

Finally, there is a need to leverage remote sensing for large-scale monitoring, given the global implications of climate intervention technologies. A partnership between the Office of the Director of National Intelligence (ODNI) and the DoD could address the challenge of collecting all available information, including the measurement data recommended above, to provide an assessment of adversary plans for large-scale climate intervention activities.

Findings and Recommendations

Finding 3

Improved sensing is needed to detect state-sponsored climate intervention activities.

Recommendation 3.1

[DoD Climate Planning Cell] Partner with ODNI, NOAA, and NASA to develop a program to measure stratospheric aerosols and particulates for improved atmospheric modeling and to prevent strategic surprise. Medium term (3-5 years).

Recommendations 3.2

[DARPA, SCO] Develop a deployable multi-purpose stratospheric aerosol and particulate sensing suite for forward-deployed units. Medium term (3-5 years).

Recommendation 3.3

[DoD Climate Planning Cell] Partner with ODNI to leverage remote sensing for monitoring large-scale climate intervention activities. Medium term (3-5 years).

Climate Intervention Sensing Example Solutions

For many decades, NOAA has maintained the ability to measure the Earth's albedo and to sense aerosols and particulates in the atmosphere using space-based observation systems. The systems provide global coverage and the sensing capability to observe large-scale SAI deployment and its impacts. For example, the Calipso satellite uses a Light Detection and Ranging (LIDAR) for aerosol measurement with a 30-m vertical and 330 m cross-track volume in an altitude range of up to 40 km sampling resolution. Global coverage is provided with a revisit rate of a particular site every 16 days. Due to spatial and temporal limitations of space-based systems, the capability does not exist to provide sufficient resolution for detecting and attributing local experiments involving SAI technologies.

Under their Earth's Radiation Budget (ERB) initiative, NOAA, in collaboration with NASA, is executing a collection campaign called SABRE to measure atmospheric aerosols and particulates using aircraft, as illustrated in Figure 27. With data collected during experimental campaigns, the SABRE project aims to understand the natural stratospheric environment and lead to improvements in the modeling of the Earth's radiation balance.

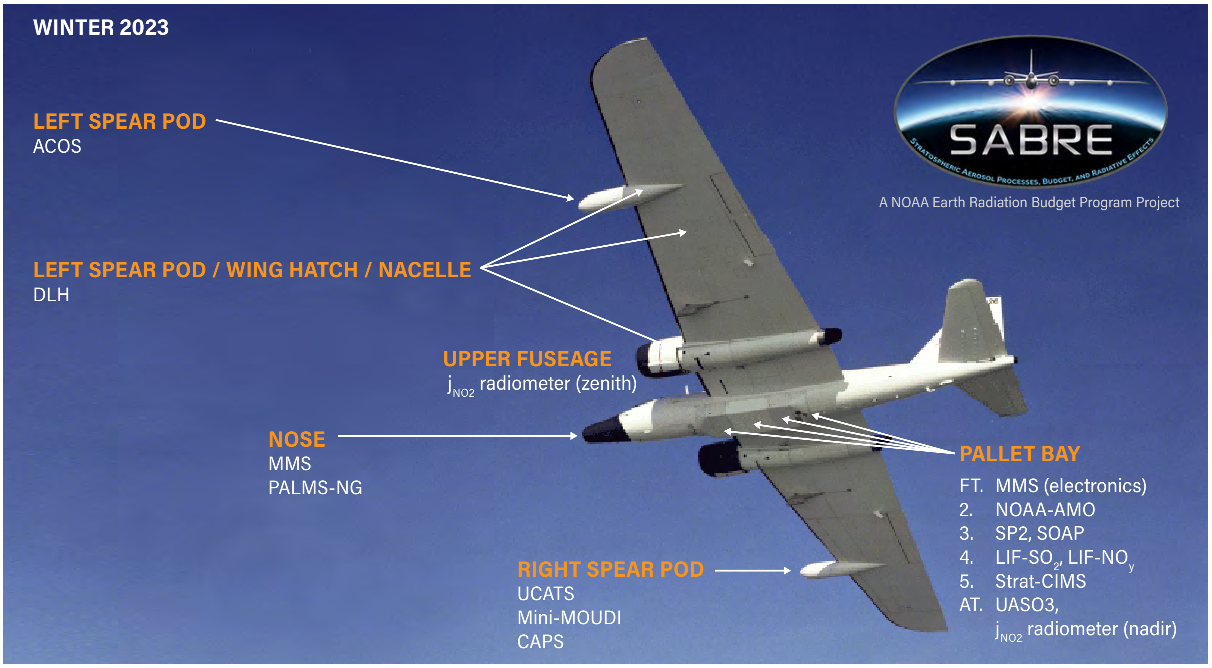

Figure 27. NOAA SABRE project aims to collect atmospheric aerosol and particulate measurements.[106]

Thus, the SABRE project provides significant information concerning atmospheric aerosols and particulates. Still, the project's campaign nature needs to provide the persistence necessary to detect local unacknowledged experimentation with SAI technologies.

Section Summary

Climate models exist, including several considered the "gold standard," e.g., Global Circulation Models and collections used by the IPCC to estimate climate risk and the Coupled Model Intercomparison Project, used by the DCAT. Integrated assessment models are potentially of greater use to the DoD because they provide details of human activity and climate interactions with the earth as a system. However, these models, all of which still have significant uncertainties, are on a global scale with low geospatial resolution. In addition, ubiquitous, global sensing across multiple domains (atmosphere, cryosphere, ocean, undersea, etc.) is needed to feed the development of these

106. Figure 27. NOAA SABRE project aims to collect atmospheric aerosol and particulate measurements. Source: NOAA Chemical Sciences Laboratory.

models and lower uncertainties. Military decision-makers and planners need more regional and local-level models. Regional models exist, but their finer resolutions increase uncertainties and require considerable computing power, which is generally lacking in the DoD (but available in other agencies). In general, global climate models that are designed for a global scale and timeline cannot easily be adapted for regional purposes and the shorter timelines that the military needs.

The amplification of climate change events will further hinder using global-scale models for military purposes. The abundance of models, predictions, and standards that are a feature of the current climate modeling environment can sow greater confusion for military decision-makers and planners who are generally not climatologists or meteorologists. In short, existing climate models lack the required timelines, detailed information for specific interest to the U.S. military, and insufficient fidelity regarding the complex dynamics of climate change. The DoD can't take this task on itself, but it should collaborate and leverage work done by other agencies (e.g., DOE, NOAA, and NASA) to address these shortfalls, including developing more accurate sub-seasonal to seasonal and seasonal climate and weather models. A Climate Planning Cell that integrates climate data from across the U.S. Government and evaluates the efficacy of existing climate models would alleviate these shortfalls. Such a cell would also assist with assimilating data sets, providing medium to long-range forecasts, quantifying uncertainties, developing early warning systems for CCMD planning, developing informed mitigation strategies, and conducting infrastructure planning and risk assessment.

In 2021, the DoD published a high-level, single-source risk assessment describing the risk of climate change to the DoD and how it intends to adapt and mitigate those risks. Even though the Department has taken multiple actions to mitigate the identified risks, it still needs to update this document. As a result, military decision-makers, planners, Allies, and partners are dealing with outdated information, particularly as Earth systems appear to be changing at an increasing rate. A triennial update would provide recent information on which military planners, allies, and partners can update their planning assumptions.

Climate literacy is important to the DoD's response to climate change. The DoD established a climate literacy sub-working group that reports to its Climate Working Group. While the sub-working group has defined climate literacy, its efforts to reach broadly and deeply into the Department have been limited. In addition, climate change has yet to be integrated into professional military education. A recent endeavor to educate faculty members across the DoD service academies and joint institutions about climate change as part of a series on the operational environment U.S. forces are likely to face is an encouraging step. Some Combatant Commands have, to varying degrees, developed programs to explain climate change issues and their impacts on military missions. All these efforts – the climate literacy sub-working group, the nascent steps to educate DoD institution faculty, and combatant commands providing exposure to climate change issues in select theaters – are important but too small given the impact of climate change already being felt by the DoD, never mind the potential for significantly more significant impacts in the future.

Climate intervention has been proposed as a means to adapt to and mitigate the impacts of climate change. For the DoD, the implications of climate intervention include not only the effect of such approaches on its military operations but also the possibility that it will have to respond to state-sponsored climate intervention activities. The DoD will have to develop the capability to monitor such activities, which includes deploying the appropriate sensing capability. Measuring stratospheric aerosols and particulates to avoid strategic surprise will be key. The DoD must also partner with other government agencies developing these modeling and sensor capabilities.

Force Readiness

Overview

Force readiness encompasses all aspects of the U.S. military's ability to conduct training and operations in every region of the globe. Climate change poses significant challenges to U.S. and partner nation readiness, both directly in terms of environmental extremes, biohazards, and increasingly severe weather conditions, and indirectly in terms of opening new operating domains (e.g., the polar regions). Consequently, it places new operational and logistical demands on personnel, equipment, and infrastructure. Of near-term concern is the threat to infrastructure due to sea level rise, subsidence, and extreme weather events.

The findings and recommendations in this chapter focus on operational and technological options to maintain and enhance force readiness in the face of large climate variations. It explores the effects on human health and performance, infrastructure, operations, and the potential for triggering events such as more HADR requests of the Department.

Human Health and Performance

State of the Science

Climate change will increasingly affect human health and performance across the spectrum of force development, generation, and employment. Examples include the potential challenge to train and operate in a highly variable range (high and low) of temperatures at basic training facilities, and as discussed previously in this report, the impact higher temperatures have on increasingly severe weather. Moreover, a rise in temperatures aggravates infectious diseases in unpredictable ways. Temperature and moisture changes can affect historical boundaries of diseases such that past infectious disease outbreaks may not be representative of future likelihoods.[107]

As temperatures and heat indices have continued to climb, human health and performance have a corresponding deleterious effect.[108] Figure 28, Figure 29, and Figure 30 show average temperature

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107. Marco Marani et al., "Intensity and frequency of extreme novel epidemics," *PNAS* 118, no.35 (2021) e2105482118, https://doi.org/10.1073/pnas.2105482118; Mora et al., "Over half of known human pathogenic diseases can be aggravated by climate change."; Sadie J. Ryan et al., "Warming temperatures could expose more than 1.3 billion new people to Zika virus risk by 2050," *Global Change Biology* 27, no. 1 (October 2020): 84-93, https://doi.org/10.1111/gcb.15384.

108. Daniel S. Moran et al., "Beating the heat: military training and operations in the era of global warming," *Journal of Applied Physiology* 135, no. 1 (July 2023): 60-67, https://doi.org/10.1152/japplphysiol.00229.2023; "Update: Heat Illness, Active Component, U.S. Armed Forces, 2019," Defense Health Agency, April 1, 2020, https://www.health.mil/News/Articles/2020/04/01/Heat-Illness-Active-Component-MSMR-2020.

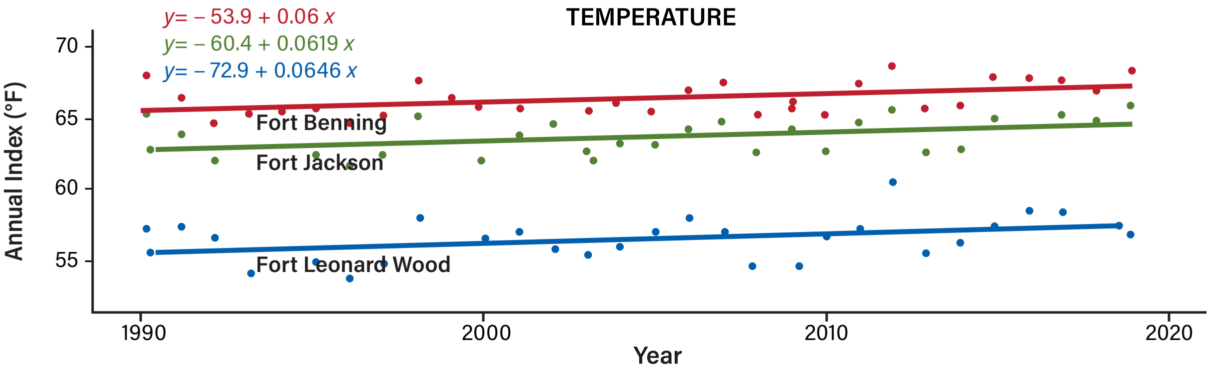


Figure 28. Trending increasing temperatures, affecting U.S. military installations.[109]

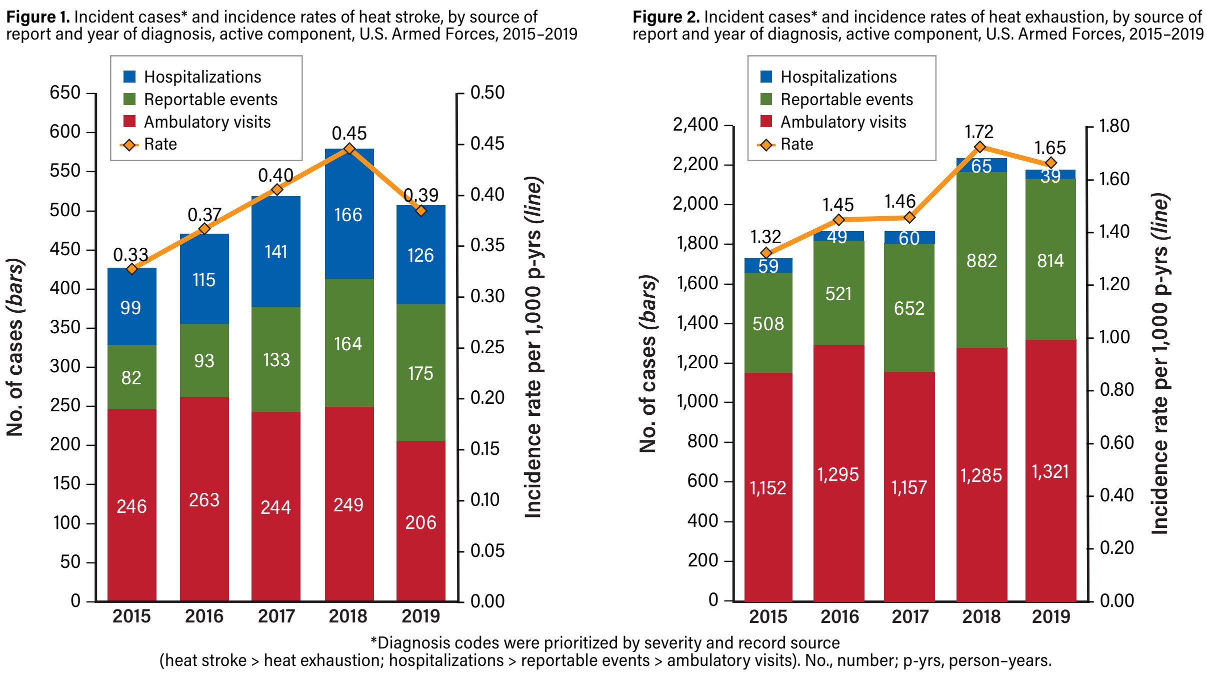


Figure 29. Increasing incidences of heat related injuries at military installations.[110]

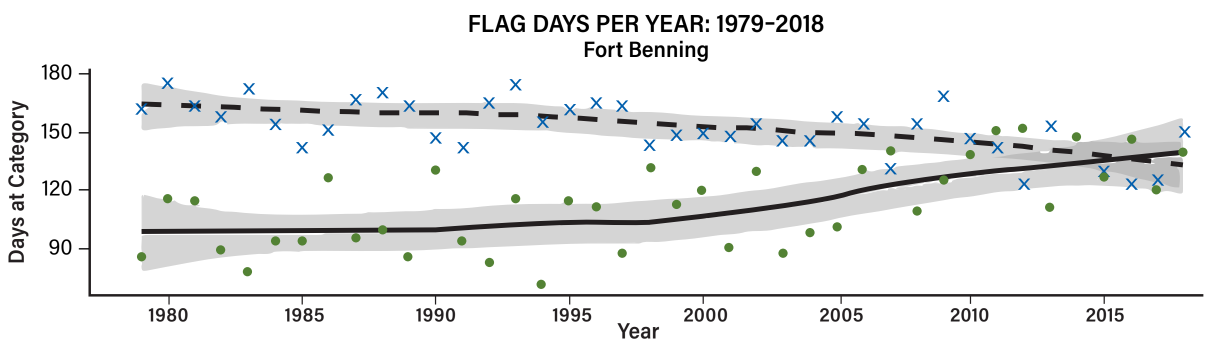


Figure 30. Flag Days historical data and trend.[111]

109. Figure 28. Trending increasing temperatures, affecting U.S. military installations. Source: C.L. Gaulin, "Beating the heat: military training and operations in the era of global warming," https://doi.org/10.1152/japplphysiol.00229.2023.

110. Figure 29 Source: Armed Forces Health Surveillance Branch Communications Team, "Update: Heat Illness, Active Component, U.S. Armed Forces, 2019"; Moran et al.

111. Figure 30 Source: "Understanding Climate Change Risks to the United States Military," Thesis, Boston University, 2019.

and heat indices across multiple military bases from 2015-2019, an increasing trend of heat-related injuries experienced by soldiers, and the generally increasing number of "black flag" days at Fort Moore (formerly Fort Benning) from 1979-2018.[112] Although lacking the data of a DoD-wide database for "black flag" days, rising temperatures will most assuredly affect both warfighter training and operations.

The science of human health, performance, and heat-related illness are active programs of study. The Army's Warrior Heat and Exertion-Related Events Collaborative (WHEC) program studies heat strain, heat strokes, and their treatments. Recent efforts have focused on furthering understanding of non-exertion related (classic) heat stroke and exertional heatstroke, the symptoms involved, the physiological and morphological factors that contribute to susceptibility, and long-term implications of survivors.[113] The Army has also contributed research to understanding treatments, such as the effectiveness of ice sheets as a clinical tool and extremity cooling.[114] Similar research is also ongoing for adaptation in cold-weather environments, such as in the Arctic. Significant work remains on both understanding human health and performance in these extremes, as well as mitigation and treatment techniques. Climate change is also necessitating changes in land use and food availability for both humans and animals. A consequence of this is exposure to new or long-extinct infectious diseases. Food availability can alter the amount of viral shedding by reservoir hosts.[115] These changes in human-reservoir host animal interactions can lead to changes in the risk of human exposure to infectious disease(s) and the likelihood of zoonotic spillover events.[116] Human migration and travel can further lead to higher risk and speedier spread as well as exposure to previously inaccessible pathogens.[117] Reports of microbial strains similar to modern bacterial pathogens as well as eukaryotic viruses being sequenced or cultured from ancient permafrost samples raise the possibility that as the permafrost thaws, such bacteria and viruses will be released. [118] The risk that these releases will lead to infection of a host is unknown in part because such studies are often avoided for biosafety reasons. However, history is replete with examples of viruses decimating previously unexposed populations.

Figure 31 plots global predictions of the number of months in a year accommodating Zika transmission, showing significant increase in areas where Zika might spread. More broadly, Figure 32 shows analysis that 78% of known pathogenic diseases could be aggravated by a change in climate.

112. A "black Flag" day is one in which the combined heat and humidity, as measured by Wet Bulb Globe Thermometer, rises above 90°F. Such a condition requires cessation of all non-essential activity, without mitigation measures.

113. Abderrezak Bouchama et al., "Classic and exertional heatstroke," *Nat Rev Dis Primers* 8, no. 1 (Feb. 2022): 8, https://doi.org/10.1038/s41572-021-00334-6.

114. David W. DeGroot, et al., "Extremity cooling for heat stress mitigation in military and occupational settings," *Journal of Thermal Biology* 38 (2013): 305–310, http://dx.doi.org/10.1016/j.jtherbio.2013.03.010.

115. Daniel J. Becker et al., "Ecological conditions predict the intensity of Hendra virus excretion over space and time from bat reservoir hosts," *Ecology Letters* 19, no. 1 (Jan. 2023), https://doi.org/10.1111/ele.14007; Caylee Falvo et al., "Diet-induced changes in metabolism influence immune response and viral shedding dynamics in Jamaican fruit bats," *bioRxiv* (Dec. 2023), https://doi.org/10.1101/2023.12.01.569121.

116. Peggy Eby et al. "Pathogen spillover driven by rapid changes in bat ecology," *Nature* 613 (2023): 340–344, https://doi.org/10.1038/s41586-022-05506-2.

117. Aidan Findlater and Isaac I. Bogoch, "Human Mobility and the Global Spread of Infectious Diseases: A Focus on Air Travel," *Trends in Parasitology* 34, no. 9 (Sept. 2018): 772-783, https://doi.org/10.1016/j.pt.2018.07.004.

118. Ann H. Reid et al., "Origin and evolution of the 1918 "Spanish" influenza virus hemagglutinin gene," *PNAS* 96, no. 4 (Feb. 1999): 1651-1656, https://doi.org/10.1073/pnas.96.4.1651; Philippe Biagini et al., "Variola Virus in a 300-Year-Old Siberian Mummy," *New England Journal of Medicine* 367 (Nov. 2012): 2057-2059, https://doi.org/10.1056/nejmc1208124; Matthieu Legendre et al., "Thirty-thousand-year-old distant relative of giant icosahedral DNA viruses with a pandoravirus morphology," *PNAS* 111, no. 11 (March 2014): 4274-4279, https://doi.org/10.1073/pnas.1320670111; Matthieu Legendre et al., "In-depth study of Mollivirus sibericum, a new 30,000-y-old giant virus infecting Acanthamoeba," *PNAS* 112, no. 38 (Sept 2015): E5327-E5335, https://doi.org/10.1073/pnas.1510795112; Jean-Marie Alempic, "An Update on Eukaryotic Viruses Revived from Ancient Permafrost," *MDPI* 15, no. 2 (2023): 564, https://doi.org/10.3390/v15020564.

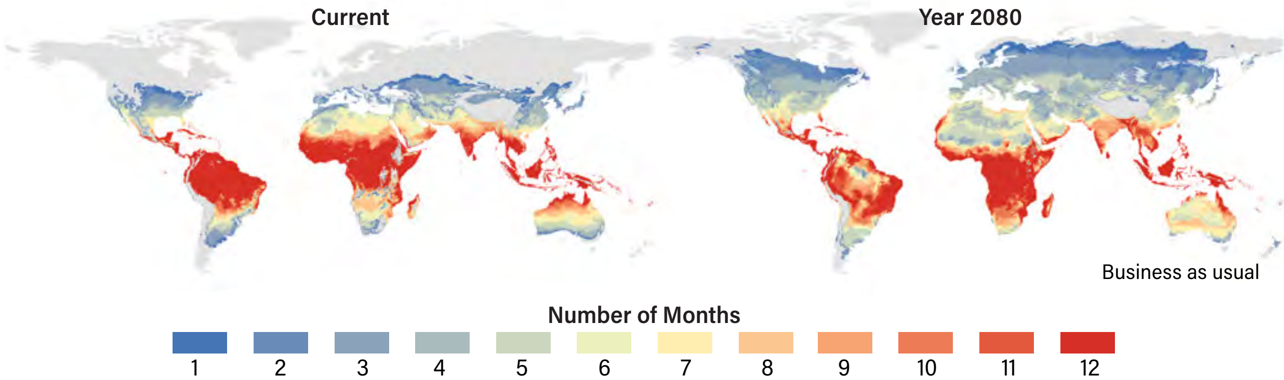


Figure 31. Global predictions of the number of months in a year with suitability for Zika transmission, showing significant increase in area where Zika might spread.[119]

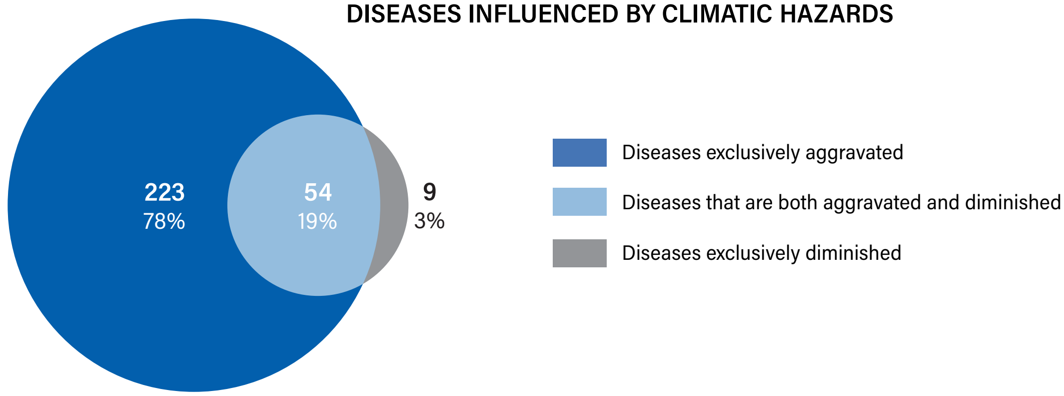


Figure 32. The majority of known human pathogenic diseases can be aggravated by climate change.[120]

The COVID-19 pandemic continues to offer lessons for technological capabilities that could effectively allow for preparation, intelligence collection, biosurveillance, understanding, protection, and mitigation of infectious disease, particularly in the case of respiratory infections. Significant work remains to understand the future disease environment in the DoD context and to mitigate the impact to the warfighter and DoD operations.

Major Gaps and Challenges

Although significant advances have been made over the last decades, notable gaps remain in understanding human health and the challenges inherent in performing in extreme environments. These range from understanding the full pathophysiology of heat and cold injuries, to development of near-term mitigation tools. Heat stress decision aids and cooling treatments, and more substantive technologies that can continuously monitor the health and individual performance, will be crucial. Monitoring technologies must provide real-time situational awareness of the force and enable significantly faster learning, in-situ interventions, and future capability/capacity development.

To address these gaps and challenges in human health and performance, the Board has three recommendations.

119. Figure 31 Source: Sadie Ryan et al., "Warming temperatures could expose more than 1.3 billion new people to Zika virus risk by 2050."

120. Figure 32 Source: Camilo Mora et al., "Over half of known human pathogenic diseases can be aggravated by climate change."

Findings and Recommendations

Finding 4

Health and human performance will be increasingly challenged by biohazards and operations in extreme weather driven by environmental climate change.

Recommendation 4.1

[Services] Accelerate the implementation of the DSB 2022 Summer Study recommendation: [USD(R&E), Assistant Secretary of Defense for Nuclear, Chemical, and Biological Defense Programs (ASD(NCB)) & Defense Health Agency (DHA)] To develop technologies for untargeted, persistent, passive, distributed, and informed biosurveillance of DoD assets with a goal of providing early warning. Engage the appropriate members of the USG, i.e., Centers for Disease Control and Prevention, National Institutes of Health, Department of State. Near term (0-2 years).

Recommendation 4.2

[Army, USD(R&E)] Build on current R&D programs focused on heat acclimation and treatment for heat-related injuries and illness (e.g., Warrior Heat & Exertion-Related Events Collaborative (WHEC) and U.S. Army Research Institute of Environmental Medicine (USARIEM)). Immediate implementation (0-1 year).

Recommendation 4.3

[Army, USD(R&E)] Accelerate R&D into adaptation efforts for cold weather operations and treatments for cold-related injuries and illness. Medium-term (3-5 years).

Health and Human Performance Example Solutions

There are several examples of successful use of biosurveillance technologies for civilian applications. First, wastewater monitoring has proven effective in early detection of SARS-CoV-2 spread.[121] Similarly, air monitoring has been demonstrated in congregate settings.[122] Second, consumer wearables technology has demonstrated early warning of respiratory infections in individuals.[123] Third, biosurveillance of travelers at airports can be used for early detection of the spread of new

121. Fuqing Wu et al., "Wastewater surveillance of SARS-CoV-2 across 40 U.S. states from February to June 2020," *Water Res.* 202, 117400 (2021), https://doi.org/10.1016/j.watres.2021.117400; Smruthi Karthikeyan et al., "Wastewater sequencing reveals early cryptic SARS-CoV-2 variant transmission," *Nature* 609 (2022): 101–108, https://doi.org/10.1038/s41586-022-05049-6; Smruthi Karthikeyan, "Rapid, Large-Scale Wastewater Surveillance and Automated Reporting System Enable Early Detection of Nearly 85% of COVID-19 Cases on a University Campus," *mSystems 6*, no. 4 (2021), https://doi.org/10.1128/mSystems.00793-21; Fabian Amman et al., "Viral variant-resolved wastewater surveillance of SARS-CoV-2 at national scale," *Nature Biotechnology* 40 (2022): 1814–1822, https://doi.org/10.1038/s41587-022-01387-y.

122. Mitchell D. Ramuta et al., "SARS-CoV-2 and other respiratory pathogens are detected in continuous air samples from congregate settings," *Nature Communications* 13, 4717 (2022), https://doi.org/10.1038/s41467-022-32406-w.

123. Ashley E. Mason et al., "Detection of COVID-19 using multimodal data from a wearable device: results from the first TemPredict Study," *Scientific Reports* 12, 3463 (2022), https://doi.org/10.1038/s41598-022-07314-0.

variants.[124] Finally, there have been reports of xenosurveillance, the next-generation sequencing and Polymerase Chain Reaction (PCR) of nucleic acid samples extracted from engorged mosquitos to identify human diseases.[125] Although several of the nucleic acid detection-based biosurveillance technologies described above have used targeted approaches to date, work is underway to develop multiplexed and/or panel based approaches that can detect multiple biothreats.[126] Adaptation of such technologies would benefit the DoD for use on mobile assets and in uncontrolled environments.

Significant efforts are ongoing within the DoD to adapt to operations and training in more extreme environments. These efforts should be accelerated and scaled. For example, the Army has significant programs focused on heat acclimation and treatment for heat related injuries and illnesses through the WHEC and at the U.S. Army Research Institute of Environmental Medicine (USARIEM) facility. In many cases, simple decision aids and tools like ice baths and ice sheets, can serve as effective heat injury prevention and treatments.[127] Deeper understanding of heat illnesses garnered through the R&D done in these programs enable a more appropriate graded approach to returning service members to duty after heat injuries.[128] Additional advanced technologies such as cooling suits and potential leveraging of commercial solutions in the sporting and athletic markets may provide advantages for the warfighter. Multiple partners in the Department, including WHEC, USARIEM, Combat Capabilities Development Command (DEVCOM), Defense Threat Reduction Agency (DTRA), DARPA, and Joint Program Executive Office (JPEO) - Chemical, Biological, Radiological, and Nuclear (CBRN) have continued to develop the use of wearables technology for continuous monitoring of human health and performance.[129] Significant opportunities exist for new and continued collaborations between these agencies and commands. The overall intent is to develop programs of record that improve heat acclimation, and watch for illnesses, biological threats, and other CBRN threats at the individual level. Figure 33 illustrates some of the kit involved and the performance monitoring that is possible.

124. Renee D. Wegrzyn et al., “Early Detection of Severe Acute Respiratory Syndrome Coronavirus 2 Variants Using Traveler-based Genomic Surveillance at 4 US Airports, September 2021–January 2022,” *Clinical Infectious Diseases*, Volume 76, Issue 3 (February 2023): e540–e543, https://doi.org/10.1093/cid/ciac461.

125. Nathan D. Grubaugh et al., “Xenosurveillance: A Novel Mosquito-Based Approach for Examining the Human-Pathogen Landscape,” *PLoS Negl Trop Dis* 9, no. 3 (2015): e0003628, https://doi.org/10.1371/journal.pntd.0003628.

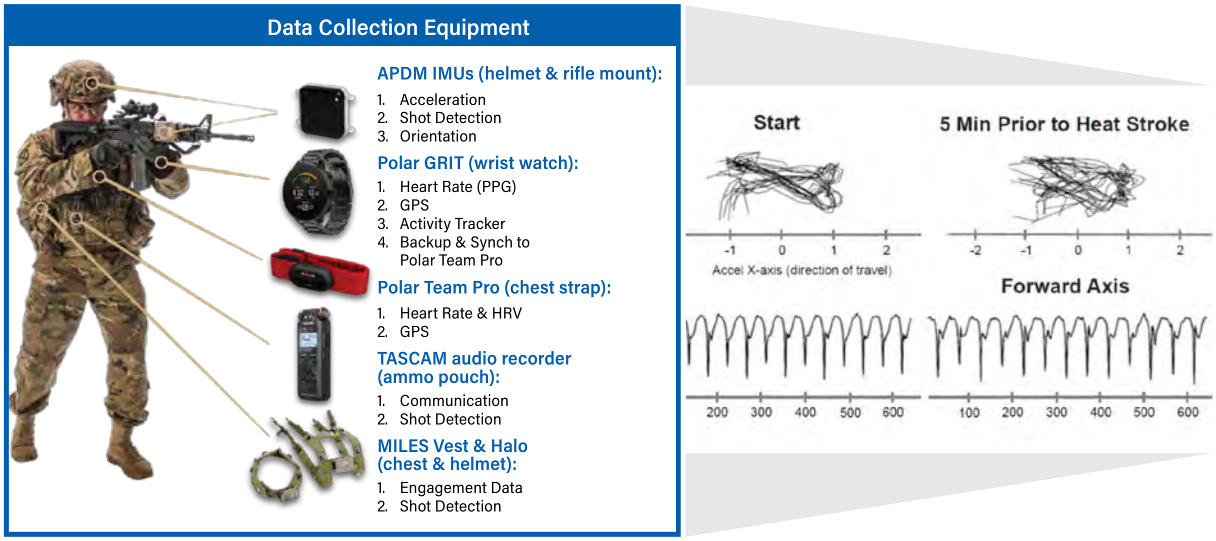
126. Cheri M. Ackerman et al., “Massively multiplexed nucleic acid detection with Cas13,” *Nature* 582, (2020): 277–282, https://doi.org/10.1038/s41586-020-2279-8; Nikhil S. Sahajpal et al., “High-Throughput Next-Generation Sequencing Respiratory Viral Panel: A Diagnostic and Epidemiologic Tool for SARS-CoV-2 and Other Viruses,” *Viruses* 13, no. 10 (2021): 2063, https://doi.org/10.3390/v13102063.

127. A.W. Potter et al, “Heat Strain Decision Aid (HSDA) accurately predicts individual-based core body temperature rise while wearing chemical protective clothing,” *Computers in Biology and Medicine* 107 (2019): 131-136, https://doi.org/10.1016/j.compbiomed.2019.02.004; DW DeGroot et al., “Cooling Modality Effectiveness and Mortality Associate With Prehospital Care of Exertional Heat Stroke Casualties,” *J Emerg Med.* 64, no. 2 (2023):175-180, doi: 10.1016/j.jemermed.2022.12.015.

128. FG. O’Connor, Y. Heled, PA. Deuster, “Exertional Heat Stroke, the Return to Play Decision, and the Role of Heat Tolerance Testing: A Clinician’s Dilemma,” *Curr Sports Med Rep.* 17, 7 (2018): 244-248, doi: 10.1249/JSR.0000000000000502. PMID: 29994825.

129. U.S. Army Medical Research and Development Command, *LOE1-focused Ignite S&T Workshop Proceedings Maximizing Human Potential Line of Effort 1: Optimize Health & Enhance Human Performance*, Technical Report No. T22-12 (Fort Dietrick, MD: MRDC, 2022), https://apps.dtic.mil/sti/trecms/pdf/AD1170349.pdf.

HUMAN PERFORMANCE EXAMPLES



Source: Army DEVCOM MASTR-E

Source: Analysis of physiological markers for heat stroke (USARIEM)

Figure 33. Examples of piloted wearables and the continuous health monitoring that is possible.

Similar efforts are ongoing to adapt to cold high latitude environments. For example, efforts at USARIEM in understanding and treating frostbite led to optimized use of clothing and managing moisture accumulation. USARIEM's efforts have resulted in practical decision aids for combat dress and foundational research in understanding genomic markers for frostbite susceptibility.[130] Additional efforts in the Department include programs like DARPA's Ice Control for Cold Environments (ICE) which aims to leverage biological adaptations to extreme cold for control of ice formation on personnel, equipment, and varied platforms.[131] These and similar efforts should also be accelerated.

Infrastructure

State of the Science

The DoD's investment in infrastructure presents a unique sustainment challenge. The annual Base Structure assessment (produced by the Office of the Assistant Secretary of Defense for Energy, Installations, and Environment) shows that the Department manages a global real property portfolio of 667,760 assets (valued at nearly $1,785 billion), on nearly 26 million acres of land, and located at 4,686 sites worldwide.[132] The buildings in this portfolio total 2.31 billion square feet. The breakdown of this infrastructure by type and across the Services is summarized in Figure 34.

130. A.W. Potter et al., "Validation of new method for predicting human skin temperatures during cold exposure: The Cold Weather Ensemble Decision Aid (CoWEDA)," *Informatics in Medicine Unlocked* 18, 100301 (2020), https://doi.org/10.1016/j.imu.2020.100301; J. W. Castellani, "Human Performance in Hot and Cold-Weather Environments," (Presentation to DSB, SA Inc. Executive Conference Center, Arlington, VA, July, 2023).

131. "DARPA's ICE Keeps Jack Frost at Bay," DARPA, Aug. 16, 2022, https://www.darpa.mil/news-events/2022-08-16.

132. Department of Defense, *Base Structure Report,* (Office of the Assistant Secretary of Defense for Energy, Installations, and Environment, 2022), https://www.acq.osd.mil/eie/bsi/BEI_Library.html.

Facilities

	Buildings		Structures		Linear Structures		Total Facilities	
	Count	PRV ($B)	Count	PRV ($B)	Count	PRV ($B)	Count	PRV ($B)
Army	135,985	$467.20	93,121	$100.31	109,336	$143.93	338,472	$711.44
Navy	59,156	$258.86	36,162	$97.78	22,454	$41.95	117,772	$398.59
Air Force	62,896	$311.32	58,925	$86.11	37,743	$109.33	159,564	$506.76
Marine Corps	26,657	$121.07	17,996	$19.43	6,449	$17.29	51,102	$157.79
Washington Headquarters Services	162	$10.91	443	$0.24	245	$0.13	850	$11.28
DoD	284,856	$1,169	206,647	$304	176,257	$313	667,760	$1,786

Buildings represent 2.31 billion square feet *PRV: Plant Replacement Value*

Figure 34. Department of Defense Real Property FY2023.[133]

Much of the DoD infrastructure is indistinguishable from civilian infrastructure, such as housing, roads and bridges, runways, buildings and associated heating, ventilation, and air conditioning systems, power generation facilities, power substations, transmission lines, communications infrastructure, water supply, and wastewater treatment facilities. Other elements of this infrastructure are unique to the DoD, such as space launch facilities, test and training ranges, and sensor systems like radars. Much of the existing infrastructure is old, with elements dating back to World War II or before, and much of the maintenance on this infrastructure has been deferred due to competing budget priorities.

Changes in temperature and humidity, sea level rise and increases in wave action, severe weather, and permafrost melt are exacerbating the challenges in maintaining this infrastructure. The subsidence of the ground level further amplifies the effects of climate change. The geographic distribution of DoD infrastructure and the location of crucial facilities in remote areas add yet another challenge to maintaining, updating, and sustaining these facilities.

Of special concern is the vulnerability of U.S. space launch infrastructure to extreme weather, particularly the Florida Space Coast. The space program is essential to U.S. national security and commercial economic interests. Warmer sea water temperatures are expected to increase the intensity of coastal storms. When coupled with sea level rise, the likelihood and impact of storm surge increase the dangers to this vital infrastructure node (Figure 35).

The reduction in Arctic ice suggests a high probability for more commercial development in the high latitudes. A scant present-day Polar presence may very well increase due to ship traffic and resource exploitation in the Arctic Ocean. The cost associated with building, maintaining, and sustaining large scale DoD infrastructure in a traditional sense is compromised by costly logistical support and dire weather. The Department would benefit from a fresh perspective on how the U.S. can maintain the capability to project power in these regions in a cost-effective and sustainable manner.

133. Figure 34 Source: Office of the Assistant Secretary of Defense for Energy, Installations, and Environment, Base Structure Report.

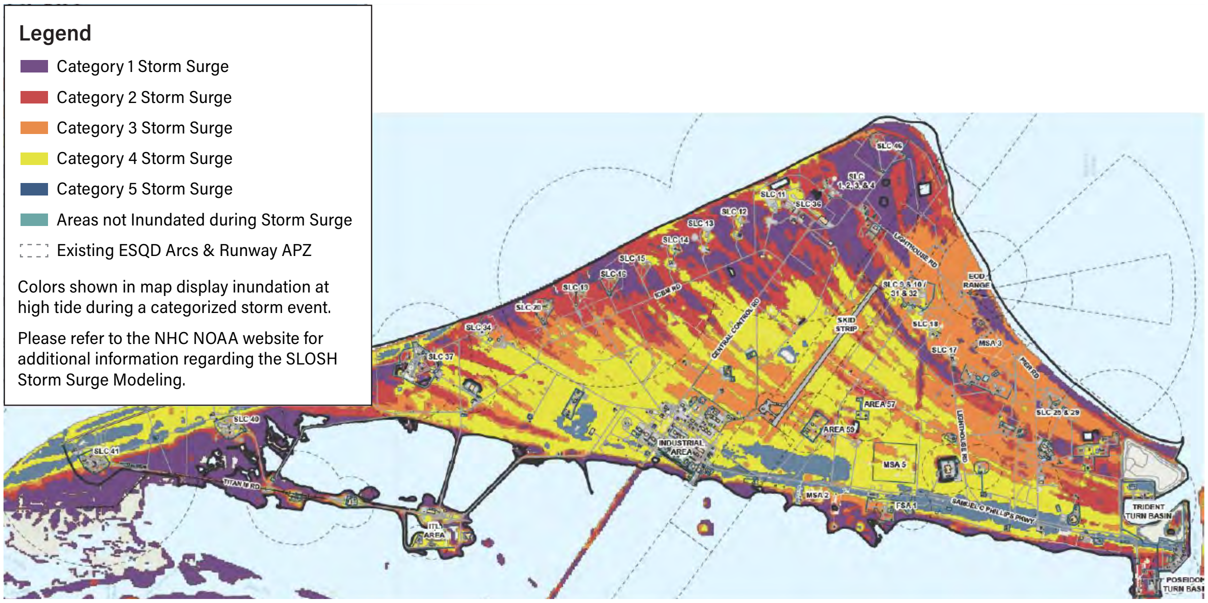


Figure 35. Inundation at high tide of space coast launch infrastructure as a function of storm surge.[134]

In summary, the DoD has a massive, decades-long investment in infrastructure worldwide whose maintenance and preservation are threatened by the effects of rapid climate change. Simply, prioritization of DoD infrastructure must be combined with effective monitoring and resilience measures to preserve high value capabilities.

Major Gaps and Challenges

Infrastructure investment in the face of changing climate is inherently challenging. The time scale for setting aside investments and the uncertainty manifest in projecting future climate effects are often incompatible and indeterminate. There are too many variables associated with climate change and the multi-variability of facilities to create a simple oversight plan. Although climate modeling continues to advance and progress is being made in downscaling these models to project localized effects, there is a level of irreducible uncertainty (both epistemic and aleatory) that limits the ability to effectively prioritize future infrastructure investment. This is referred to as decision making under deep uncertainty.[135] In such cases, decision making relies less on "predict then act" and more on "monitor and adapt."

Providing reliable power to bases in remote areas is a special challenge. Many existing remote bases rely on diesel generators for electrical power. The infrastructure required to supply fossil fuels (ports, roads, pipelines, tanker ships, security, and trucks) in these remote areas is a formidable challenge. Moreover, a non-routine diesel delivery, for instance, can become a burdensome intelligence shortcoming (logistics often portend operations). Also, Arctic fuel deliveries, for instance, warrant secondary capabilities (like ice breakers). History has shown that these supply chains for fossil fuels can be especially vulnerable in times of global crisis, as well. Advances in the development of nuclear power, specifically microreactors, provide an attractive alternative for powering remote bases such

134. Figure 35 Source: NHC NOAA.

135. Vincent A.W.J. Marchau et al., *Decision Making under Deep Uncertainty: From Theory to Practice*, (Springer Cham, 2019), https://doi.org/10.1007/978-3-030-05252-2.

as those in northern climes (i.e., Alaska and Greenland). Small electrical power plants would be especially valuable in emergency scenarios, possibly even significant HADR locations, to provide standup electrical power. Remote military facilities, ground-based radar systems and forward-deployed Joint Task Forces are other situations warranting further study of the concept.

There are also alternatives to expanding DoD's common infrastructure. Techniques to maintain the U.S. presence through remote monitoring and stand-off power projection may also provide an option to limit the need for physical infrastructure expansion in remote regions. Intriguing possibilities for locations with questionable long-term commitment include modular structures and/or expansion of the Expeditionary Sea Base concept.

Findings and Recommendations

Finding 5

A global strategy for facilities management and infrastructure resilience is needed to contend with climate change's extreme weather.

Recommendation 5.1

[USD(P), Under Secretary of Defense for Acquisition and Sustainment (USD(A&S)), and Joint Staff] Expand federal programs to undertake a DoD-wide integrated prioritization of bases and facilities most at risk of climate change and of highest mission importance. Near term (0-2 years).

[SERDP-ESTCP, USD(R&E), United States Army Corps of Engineers (USACE)] Spearhead development of resilient, structural self-healing, and hybrid barrier materials for at-risk DoD facilities. Consider leveraging DARPA BRACE, DARPA Reefense, and USACE Engineering with Nature initiatives. Near term (0-2 years).

[ASD(EI&E)] Leverage technologies to monitor and alert of failing defense infrastructure (e.g., Coherent Change Detection (CCD) Synthetic Aperture Radar (SAR)). Medium-term (3-5 years).

[ASD(EI&E), USD(R&E)] Assess alternative basing constructs to address the risks posed by climate change to installations and forward bases. Near term (0-2 years).

Recommendation 5.2

[USD(A&S)] Accelerate acquisition, certification, and deployment of independent power sources, such as nuclear microreactors, and prioritize NORTHCOM microreactor demonstrator at Eielson AFB, Alaska (2026 demo). Medium-term (3-5 years).

Recommendations 5.3

[United States Space Force (USSF) S5/S8] Develop contingency national security space launch options to existing climate-threatened coastal facilities. Medium-term (3-5 years).

Infrastructure Example Solutions

To aid in planning in "deep uncertainty" conditions, the U.S. Army Corps of Engineers uses a Dynamic Adaptive Policy Pathway in their Climate Risk Informed Decision Analysis (CRIDA) methodology.

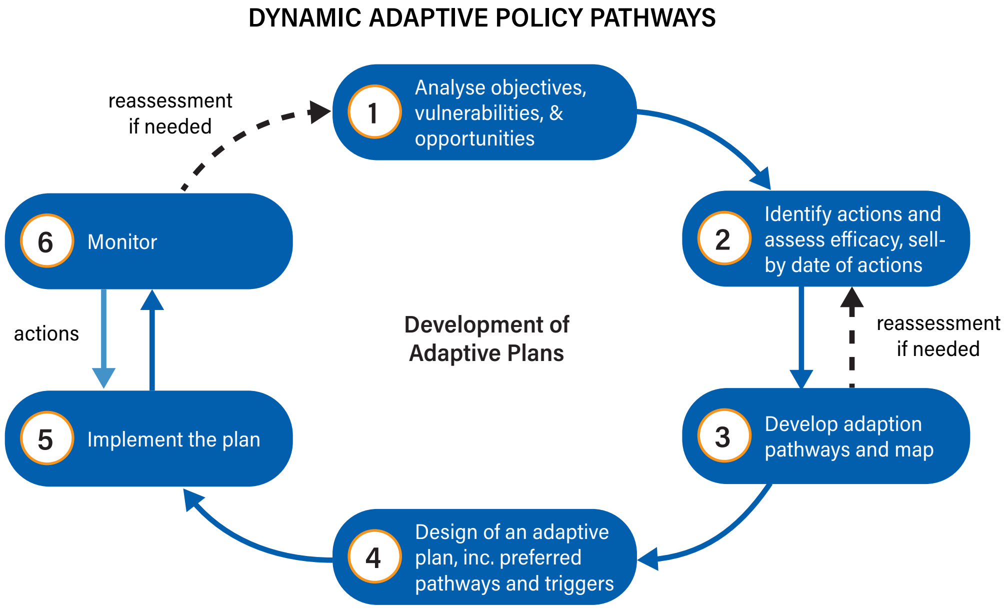


Figure 36. Dynamic Adaptive Policies Pathway.[136]

Synthetic Aperture Radar (SAR) is a useful tool in remote sensing due to its ability to form high resolution images with relative invariance to weather and lighting conditions. Comparing SAR images/data using magnitude (or amplitude) and phase to estimate the coherence between two images is called Coherent Change Detection (CCD). Hence, Coherent Change Detection-Synthetic Aperture Radar (CCD SAR) is a viable way to monitor structural integrity of infrastructure. Such monitoring can be helpful in infrastructure investment decisions.

DARPA has two ongoing infrastructure monitoring programs that may become programs of record. The Bio-inspired Restoration of Aged Concrete Edifices (BRACE) program aims to prolong the serviceability of DoD structures and airfield pavements by integrating a self-repair capability into existing concrete.[137] Leveraging these enhancements and new methodologies for structures and materials could greatly increase the life of these facilities and offset the adverse effects of sea level rise and water intrusion.

The DARPA Reefense Program seeks to develop self-healing, hybrid biological and engineered reef-mimicking structures to fight coastal flooding, erosion, and storm damage. Contracts have been awarded to begin assessing its viability.[138]

136. Figure 36 Source: Ariane Pinson, USACE Presentation to DSB, June 21, 2023.

137. "Concrete in Disrepair? DARPA May Help You BRACE It," DARPA, March 23, 2023, https://www.darpa.mil/news-events/2023-03-23.

138. "X-REEFS": neXt generation Reef Engineering to Enhance Future Structures," University of Miami, https://x-reefs.earth.miami.edu/.

Figure 37. Black Hawk helicopters land on Expeditionary Sea Base USS Lewis B Puller (ESB 3) in the Arabian Gulf.[139]

Interior-to-the U.S. and island launch options minimize space launch interruptions or even program collapse by providing DoD space launch options. Sea launch options have an attractiveness to further minimize risk. For a national emergency, launch options outside of currently accepted range safety constraints at existing launch facilities should be explored, as well. It is important to note that launch infrastructure vulnerability affects military *and* commercial needs, thereby affecting the entire U.S. economy.

The Expeditionary Sea Base (ESB) is designed as a highly flexible forward staging base for operations that can provide support to an array of operations.[140] The ship can support second tier operations such as counter-piracy, maritime security, and humanitarian and disaster relief. The platform supports nearly all U.S. rotary wing aircraft and has been deployed since 2017. Assessments of the ESB have shown that its utility can be broadened.[141] Continued development of the ESB and similar concepts can provide an option to support U.S. forces in regions of the world where there is not a permanent presence. A renewed look at the viability of larger sea bases capable of fixed wing operations and long-term presence is the logical progression of the ESB.

Climate change is increasingly challenging supply lines to remote facilities. In most facilities, standalone electrical power generation is provided by banks of diesel generators. The delivery of fossil fuels ranks as food and water for highest priority at every forward operating location, and often, the irregular delivery of fuel alerts an adversary of an impending operation. Hence, an alternative to critical fuel deliveries is to leverage the commercial development of microreactors (<20 MWe) and small modular reactors (20-300 MWe) for electrical power generation. SCO kicked off Project Pele in 2022 to leverage commercial advances for DoD mobile power applications, in such locations as remote radar warning sites and forward deployed bases.[142] The planned Pele reactor is an Advanced

139. Figure 37 Source: Photo by Staff Sgt. Timothy Clegg, U.S. Navy Military Sealift Command.

140. "Expeditionary Sea Base," U.S. Navy, https://www.msc.usff.navy.mil/Ships/Ship-Inventory/Expeditionary-Sea-Base/.

141. Daryle Cardone, Ben Coyle, and Daniel Murphy, "Assessing the Expeditionary Sea Base," *US Naval Institute* 149/1/1,439 (Jan. 2023), https://www.usni.org/magazines/proceedings/2023/january/assessing-expeditionary-sea-base.

142. Jeff Waksman, "Project Pele Overview: Mobile Nuclear Power For Future DoD Needs," May, 2022, https://www.nrc.gov/docs/ML2212/ML22126A059.pdf.

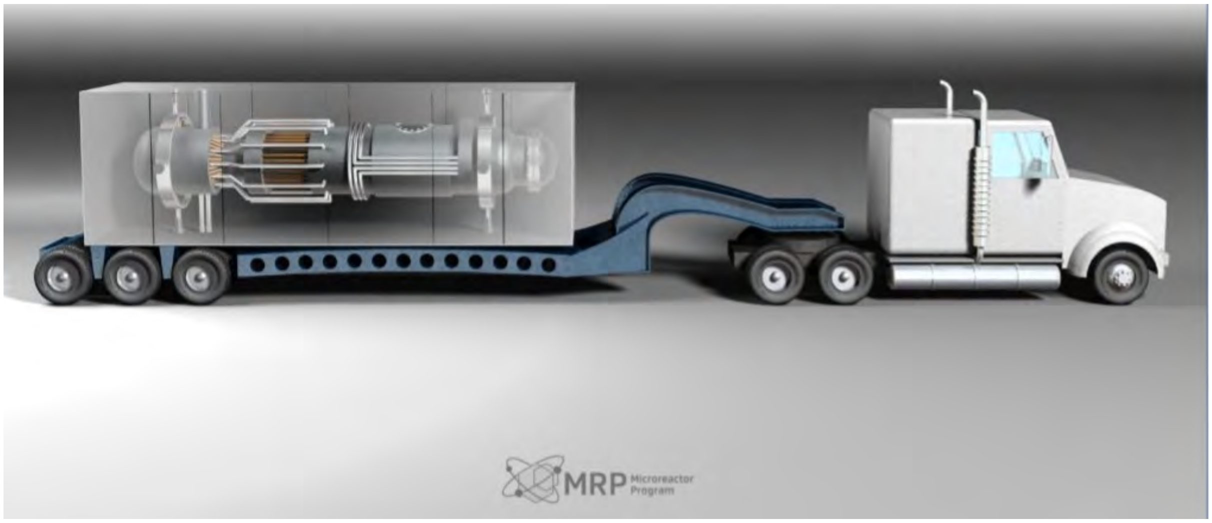


Figure 38. Portable power.[143]

Gas Reactor (AGR) design incorporating advanced Tristructural Isotropic (TRISO) encapsulated nuclear fuel for safe operations, and is intended to be air transportable, Conex box sized. NORTHCOM is moving forward with a demonstration of a 5MWe microreactor at Eielson Air Force Base (AFB), Alaska (planned demo 2026). The reactor will be privately NRC-Licensed, funded and operated for the DoD under a power-purchase agreement.[144] The DoD is well positioned to lead the certification process of small nuclear reactors due to the success of the U.S. Navy's nuclear propulsion program. Commercial adoption of grid-augmenting small nuclear reactors has high potential in the U.S. and abroad. Further advances and acceptance may lead to microreactor power plants being more broadly employed in remote areas and used to restore a localized power grid after a natural disaster.[145]

Extreme Environments (Polar, High-Temperature)

State of the Science – Polar

Sea Ice Thickness/Extent

An obvious effect of climate change is a receding Arctic ice cap and a corresponding reduction of ice accumulations on land. It is estimated that the Arctic is warming four times faster than other regions of the world.[146] Current projections suggest that the Arctic will be navigable (partially ice-free) in the summer by the 2030s, even under lower emission scenarios; previous projections indicated that such conditions would not become possible until the 2050s.

143. Figure 38 Source: Idaho National Laboratory, https://inl.gov/trending-topics/microreactors/.

144. "Micro-Reactor Pilot Program," Eielson Air Force Base, https://www.eielson.af.mil/microreactor/.

145. Constance Jenkins (NORAD/NORTHCOM Presentation to DSB, SA Inc. Executive Conference Center, Arlington, VA, July 19, 2023).

146. Yeon-Hee Kim et al., "Observationally-constrained projections of an ice-free Arctic even under a low emission scenario," *Nature Communications* 14, 3139 (2023), https://doi.org/10.1038/s41467-023-38511-8.

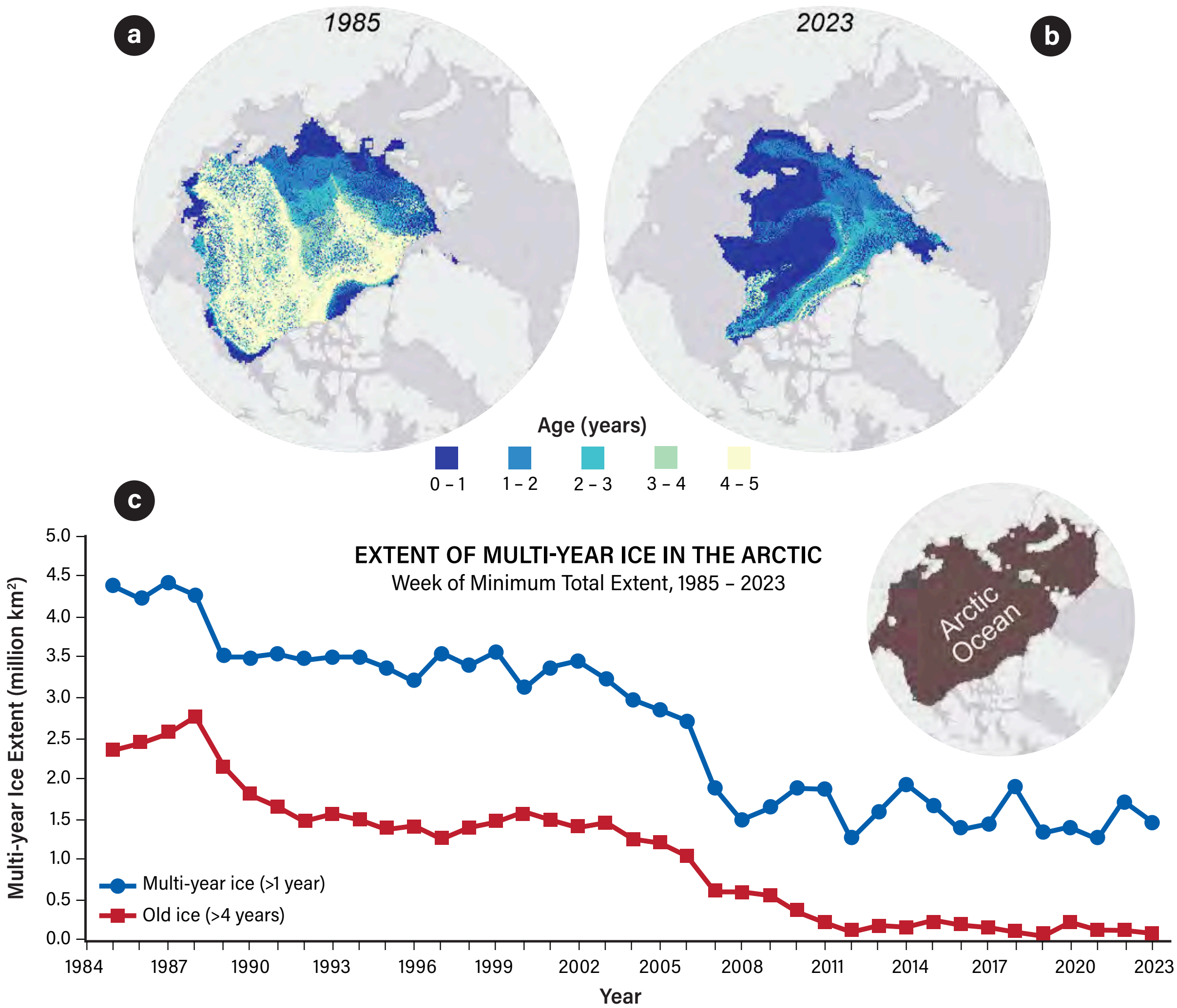


Figure 39. Landmass changes.[147]

Arctic Cyclones

Observations have documented an increasing frequency of high latitude cyclones. Polar cyclones, although infrequently discussed, are increasing in frequency, intensity, and duration.[148] Although storms in the high north are common, the frequency and ferocity of these storms may be precursors to increasing melting of land and sea ice.

Permafrost Collapse

Permafrost is the perennially frozen soil that covers about 25% of the land in the Northern Hemisphere, particularly in Canada, Russia, and Alaska. These frozen soils have historically maintained the structural integrity of facility foundations in the high latitudes, "similar to load-bearing support

147. Figure 39 Source: NOAA Arctic Report Card 2023, https://arctic.noaa.gov/report-card/report-card-2023/sea-ice-2023.

148. X. Zhang, H. Tang, J. Zhang et al., "Arctic cyclones have become more intense and longer-lived over the past seven decades," *Commun Earth Environ* 4, 348 (2023), https://doi.org/10.1038/s43247-023-01003-0.

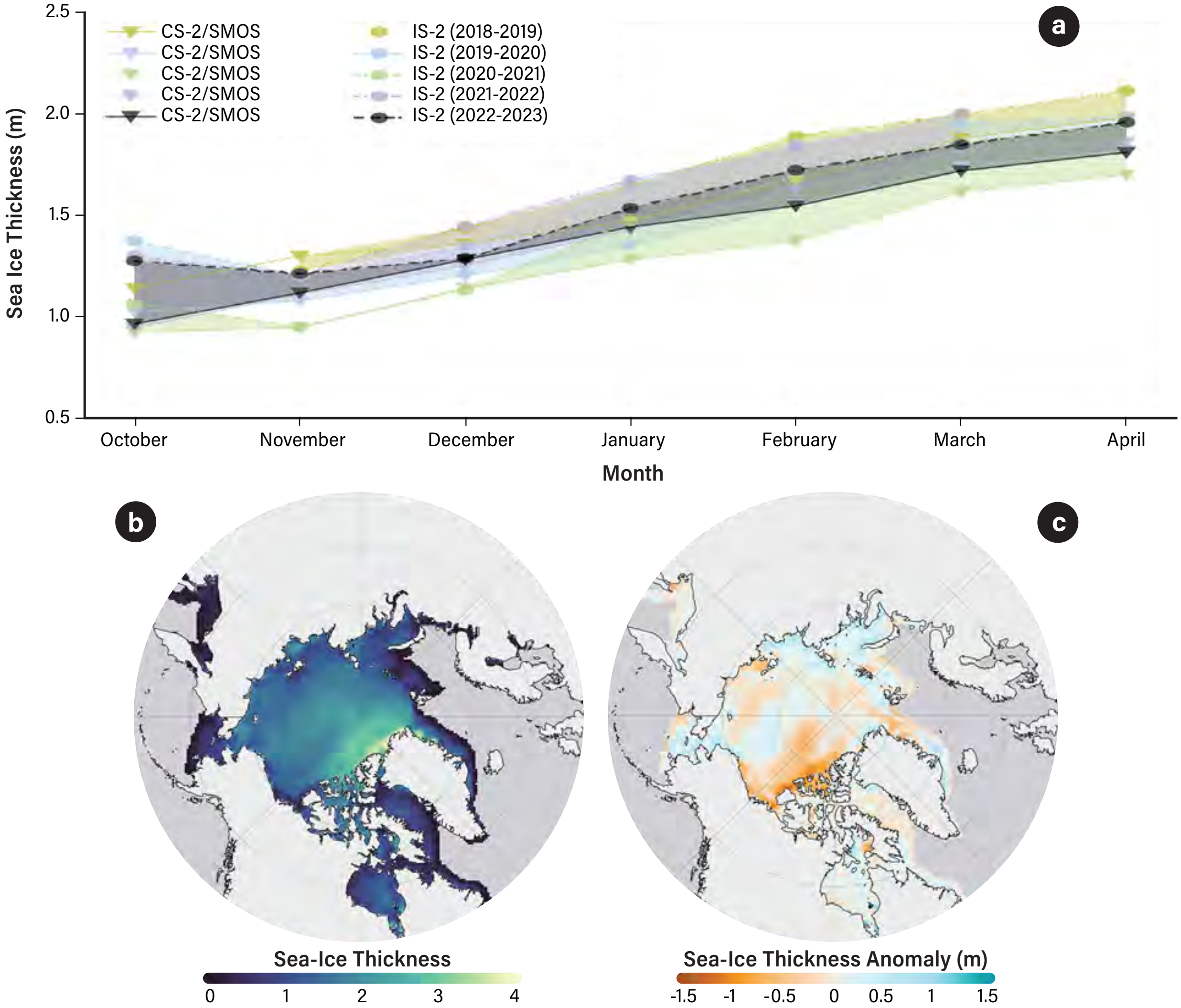


Figure 40. Sea ice changes and anomalies.[149]

beams in buildings."[150] However, as global temperatures rise and patterns of precipitation change, the permafrost is becoming vulnerable to thaw, which causes heaving and collapse. One study showed that the destabilized land surfaces have increased by > 300% over historical trends in the past two decades.[151]

In addition, when the ground thaws, microbes begin feasting on organic matter in soils that have been frozen for millennia. These microbes release carbon dioxide and methane; as these gases escape into the atmosphere, they further warm the climate, creating an amplifying feedback loop for global warming.[152] As previously noted, there is also the potential for the release of pathogens that humans may be unprepared to mitigate.[153]

149. Figure 40 Source: NOAA Arctic Report Card 2023, https://arctic.noaa.gov/report-card/report-card-2023/sea-ice-2023/.

150. Mark J. Lara, "Driven by climate change, thawing permafrost is radically changing the Arctic landscape," *PBS*, April 13, 2022, https://www.pbs.org/newshour/science/driven-by-climate-change-thawing-permafrost-is-radically-changing-the-arctic-landscape.

151. Lara, "Driven by climate change, thawing permafrost is radically changing the Arctic landscape."

152. Lara, "Driven by climate change, thawing permafrost is radically changing the Arctic landscape."

153. Lara, "Driven by climate change, thawing permafrost is radically changing the Arctic landscape."

Electromagnetic (EM) Wave Propagation

There has been limited research on the impact of climate change on the propagation of EM waves in the Arctic. Such waves fall into two regimes: a few MHz to tens of MHz whose propagation is dominated by ionospheric and surface wave effects, and hundreds of MHz and higher that are dominated by tropospheric conditions. Other than studies of ionospheric effects on Medium Frequency/High Frequency (MF/HF) radio waves in the Arctic, "Not much is known about the RF (Radio Frequency) propagation environment in the Arctic and how communications and radar systems behave there with little measured data and uncertainty in the accuracy of weather models in the region."[154]

As part of the ONR-funded 2018 Stratified Ocean Dynamics in the Arctic (SODA) campaign, researchers measured various HF and microwave signals of opportunity during a U.S. Coast Guard (USCG) icebreaker operation. While HF signal propagation experienced expected ionospheric dependencies, instances of anomalous tropospheric propagation effects were observed. In addition, the increasingly dynamic sea-ice-land boundary impacts RF ducting and increases radar clutter.

Optical propagation in the Arctic will also be affected due to increased sea fog frequency (SFF) especially in areas of retreating sea ice. A recent study detailed transit times for the Northwest Passage (NWP) and the Northern Sea Route (NSR) under different emission scenarios and found that the sea fog would cause an increase in delays of 23-27% for the NWP and 4-11% for the NSR.[155] Beyond the navigation effects, the presence of increased sea-fog in these areas would degrade EO/IR sensing effectiveness with present technologies.

Acoustic Propagation

The sound velocity profile (SVP) in the Arctic Ocean has historically shown a monotonically increasing sound speed with depth, guiding sound waves from a source up to the surface after bending upward at depth; there, those sound waves reflect off the ice pack, and repeat the process downrange until the sound pressure level is undetectable. However, water density differences caused by melting sea ice or freshwater runoff (less dense fresh water) causes a localized SVP that traps sound waves in surface ducts. Consequently, undersea acoustic detection and communications present new challenges to operations (see Figure 41 on next page).[156] A surface duct greatly increases the probability of detection of a submarine at shallow depths, for instance.

Major Gaps and Challenges – Polar

A reduction of Arctic ice will increase commercial shipping and resource exploitation in the far north. Already, international disagreements on commercial activity and counter sovereignty claims are in the news.

154. Z. K. Burchfield et al., "RF Propagation Characterization in the Arctic: Measurements from JHU/APL participation in 2018 SODA campaign," *2019 USNC-URSI Radio Science Meeting (Joint with AP-S Symposium)*, Atlanta, GA, USA, 2019, 51-52, doi: 10.1109/USNC-URSI.2019.8861940.

155. S. Song et al., "Adapting to a foggy future along trans-Arctic shipping routes," *Geophysical Research Letters* 50, e2022GL102395 (2023), https://doi.org/10.1029/2022GL102395.

156. H. Schmidt and T. Schneider, "Acoustic communication and navigation in the new Arctic — A model case for environmental adaptation," *2016 IEEE Third Underwater Communications and Networking Conference (UComms)*, Lerici, Italy, 2016, 1-4, doi: 10.1109/UComms.2016.7583469.

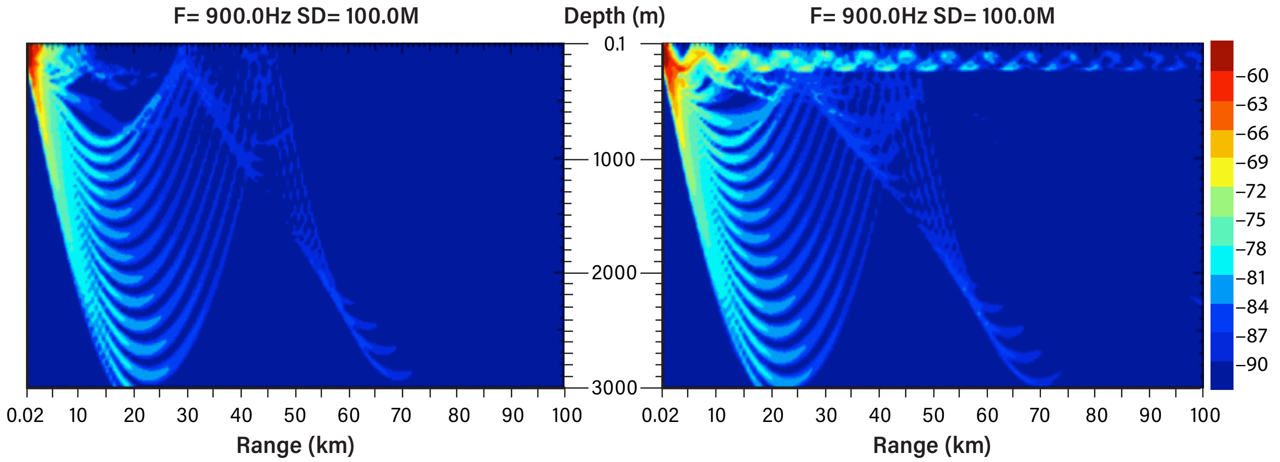


Figure 41. Undersea acoustic detection.[157]

Icebreakers

The U.S., plus its Arctic allies (Sweden, Denmark, Norway, Finland, Iceland, Canada) significantly lag behind Russia in icebreaking capabilities that would be necessary for expanded surface operations and mobile Arctic operational support.[158]

A tally of ice breakers is found in Figure 42.

Notably:

- Russia has eight active heavy icebreakers (all nuclear), four heavy icebreakers in various stages of construction, and four more heavy icebreakers planned (all appear to be nuclear, but construction has slowed since the invasion of Ukraine).[159]
- Arctic Region Allies have one active heavy icebreaker (non-nuclear); the USCG has three heavy icebreakers planned or under construction (all conventional propulsion). Canada has one medium or heavy icebreaker planned.[160]
- China has two heavy icebreakers planned (one nuclear). None are known to be under construction as of this writing.[161]

China's increased investment and frequent operations in the region are often welcomed by U.S. Allies and other nations worldwide. Chinese investment is seen as an assurance that business in the Arctic and through the Arctic is on the upswing equating to less expensive transit times in the future.[162]

157. Figure 41 Source: NOAA Arctic Report Card 2023, https://arctic.noaa.gov/report-card/report-card-2023/sea-ice-2023/.

158. In US parlance, "heavy icebreakers" are icebreakers capable of breaking ice up to 6 feet (1.8 m) thick at a speed of 3 knots. Ronald O'Rourke, *Coast Guard Polar Security Cutter (Polar Icebreaker) Program: Background and Issues for Congress,* CRS Report No. RL34391 (Washington, DC: Congressional Research Service, 2024), https://crsreports.congress.gov/product/pdf/RL/RL34391.

159. O'Rourke, *Coast Guard Polar Security Cutter (Polar Icebreaker) Program: Background and Issues for Congress.*

160. O'Rourke, *Coast Guard Polar Security Cutter (Polar Icebreaker) Program: Background and Issues for Congress.*

161. Trym Eiterjord, "Checking Back in on China's Nuclear Icebreaker," *The Diplomat*, February 13, 2023, https://thediplomat.com/2023/02/checking-back-in-on-chinas-nuclear-icebreaker/.

162. Jeremy Greenwood, "The Polar Silk Road will be cleared with Chinese icebreakers," Brookings, Nov. 24, 2021, https://www.brookings.edu/articles/the-polar-silk-road-will-be-cleared-with-chinese-icebreakers/.

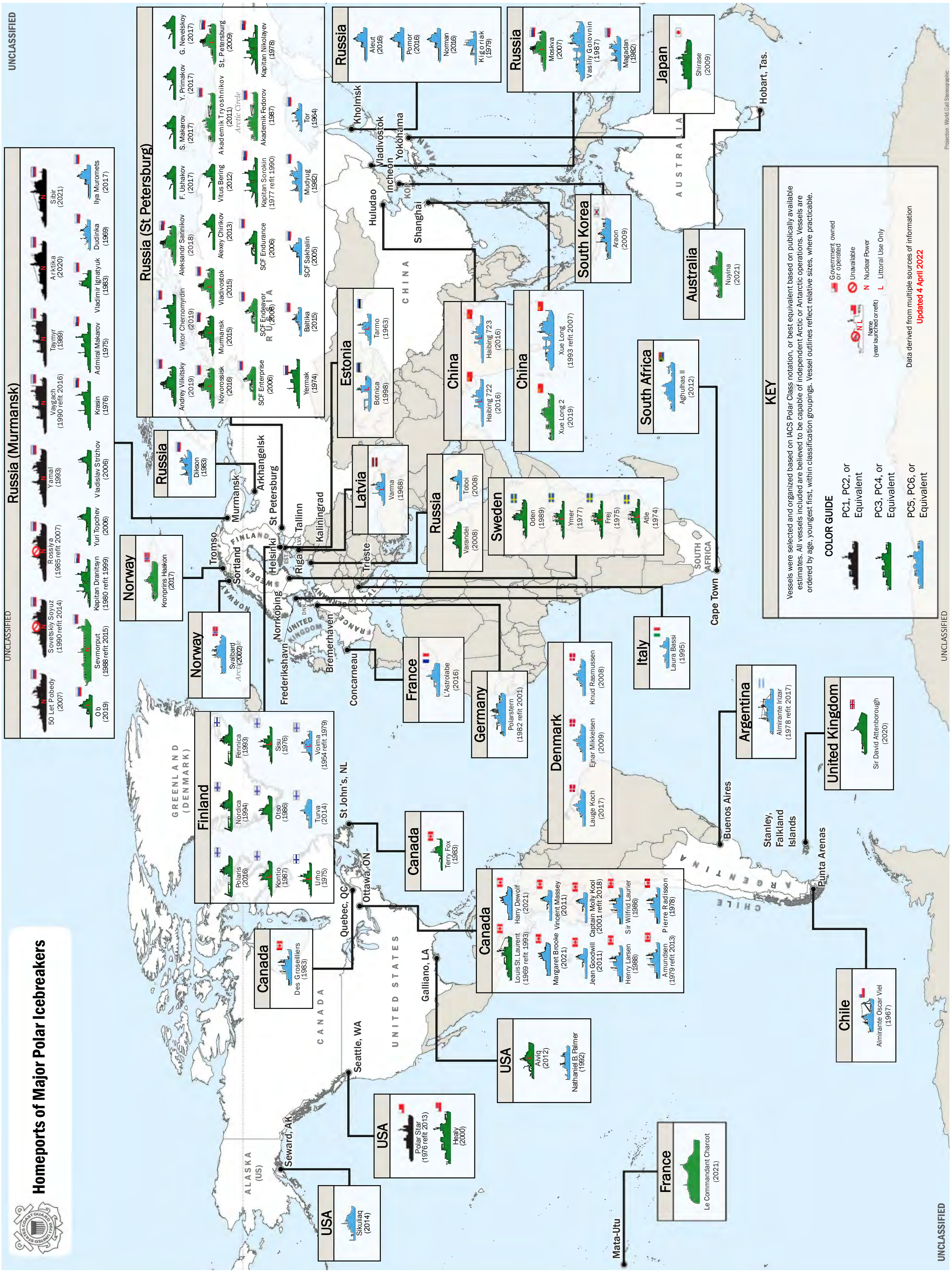


Figure 42. Icebreaker distribution.[163]

The U.S. Coast Guard, in its FY2013 budget, initiated the Polar Security Cutter (PSC) program to acquire new heavy polar icebreakers. The Coast Guard envisages procuring at least three new PSCs followed by the procurement of at least three Arctic Security Cutters (ASCs, i.e., medium polar icebreakers). The design and construction of the first PSC has been delayed; it may now be delivered to the Coast Guard no earlier than 2028. The Coast Guard's proposed FY2024 budget requests $170.0 million in continued procurement funding for the PSC program.[164] The Coast Guard testified in April, June, and November 2023 that a new Coast Guard fleet analysis concluded that the service would require a total of eight to nine polar icebreakers, including four to five heavy polar icebreakers and four to five medium polar icebreakers, to perform its projected polar (i.e., Arctic and Antarctic) missions.[165]

The Coast Guard is also seeking to acquire a commercially available icebreaker to complement existing polar icebreaking cutter capabilities and increase near-term Arctic presence before the first Polar Security Cutter delivery date.[166] The needs for an "Allied" mix in icebreakers should be balanced in aggregate to support the increased military and commercial leverage of the Arctic region. As the U.S. Coast Guard has icebreaking responsibility, they are integral to planning U.S. and Allied capability in the Arctic. The future force mixes to provide the commercial and operational capability to operate in the Arctic is an ongoing subject of debate in military shipbuilding circles. Whether the increased peer adversary presence in the Arctic warrants an uptick in U.S. ice breaker construction remains to be seen.

Ice-hardened Platforms

If increased presence missions in the Arctic are possible, U.S. military platforms must be appropriately hardened for the environment. Ice accretion is a particular challenge for ships and aircraft. For ships and offshore structures, the primary sources of ice accretion are sea spray and precipitation. Sea spray freezing on a platform can result in unsafe topside conditions and changes to the mass, center of gravity, and hydrostatic restoring moments. Reduced performance and damage to antennae and other topside sensor systems is highly problematic.[167] The warming of the sea surface and less sea ice does not lessen the accumulation of topside icing on ships. Logically, more heat in the Arctic may induce more high winds and icing. The design of platforms for the polar regions must account for these issues, and improved surface coating technologies will be required to mitigate ice accretion.

Ice-hardened hulls may also be required to enable sustained Arctic operations. Ice hardening features may include double hulls, thicker hulls, hull strengthening, protected rudders and propellers, sea water inlets/outlets protection, hardened hull contact points, and ice belts.[168]

163. Figure 42 Source: US Coast Guard.

164. Ronald O'Rourke et al., *Changes in the Arctic: Background and Issues for Congress,* CRS Report No. R41153 (Washington, DC: Congressional Research Service, 2024), https://crsreports.congress.gov/product/pdf/R/R41153/199.

165. "Report to Congress on Coast Guard Polar Security Cutter," U.S. Naval Institute, Jan. 18, 2024, https://news.usni.org/2024/01/18/report-to-congress-on-coast-guard-polar-security-cutter-23.

166. United States Coast Guard, *Arctic Strategic Outlook Implementation Plan* (Washington DC: United States Coast Guard, 2023), https://media.defense.gov/2023/Oct/25/2003327838/-1/-1/0/ARCTIC%20STRATEGIC%20OUTLOOK%20IMPLEMENTATION%20PLAN%20508%20COMPLIANT.PDF.

167. Shafiul Mintu and David Molyneux, "Ice accretion for ships and offshore structures. Part 1 - State of the art review," *Ocean Engineering* 258, 111501 (2022), https://doi.org/10.1016/j.oceaneng.2022.111501.

168. "Ice-Strengthened Vessels: An Overview of the Ice Class," My Vessel Logs, Feb. 14, 2014, https://www.myvessellogs.com/blog/Ice-Strengthened-Vessels-An-Overview-of-the-Ice-Class.

Command, Control, Computers, Communications, Cyber, Intelligence, Surveillance, and Reconnaissance (C5ISR)

Many subjects touch upon the ability of the force to navigate, communicate, and surveil. As previously noted, there is a lack of understanding of the impact of climate-change driven effects on EM wave propagation in the Arctic. Available open-source data is from a limited number of opportunistic measurements (e.g., ONR SODA 2018). There is a need for a temporal mapping of the EM spectrum in the Arctic environment under a variety of conditions for operational and system design purposes. Similarly, there is a need for ongoing understanding of the acoustic environment in the Arctic basin to optimize underwater sensing and communications capabilities. Also, the Northern Warning System radar sites are increasingly at risk due to coastal erosion and permafrost collapse.[169]

Lastly, C5ISR (Position, Navigation, and Timing (PNT)) satellite coverage over the poles must be carefully evaluated. Polar/Sun Synchronous and Highly Elliptical orbits (HEO) can provide sustained coverage of the poles during portions of their orbits.

State of the Science – High Temperatures

A voluminous amount of scientific data shows that as global temperatures have increased, ocean temperatures increase, and ocean salinity variations become more pronounced. Figure 43 illustrates an example of the prevalence of highest recorded temperatures for 2022 compared to the 30-year average temperatures between 1991 and 2020.

Additionally, Figure 44, Figure 45, and Figure 46 provide recent data from the NOAA and the Environmental Protection Agency (EPA) that capture long-term trends in land (both Continental United States (CONUS) and global) and ocean temperatures.[170] These conditions can exceed nominal operating parameters and shorten the lifespan of equipment.

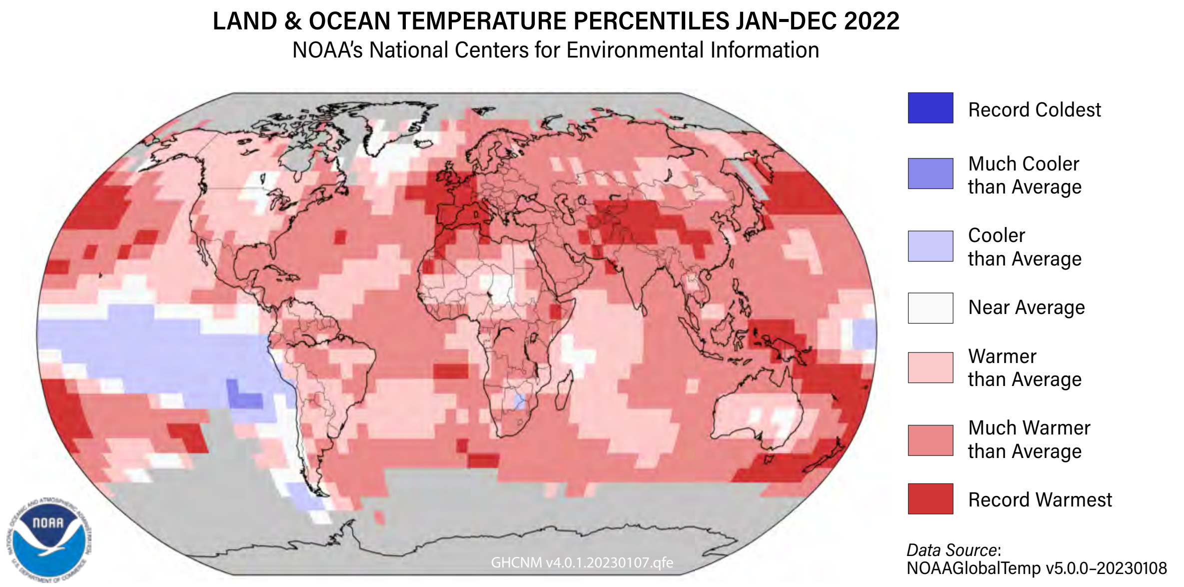
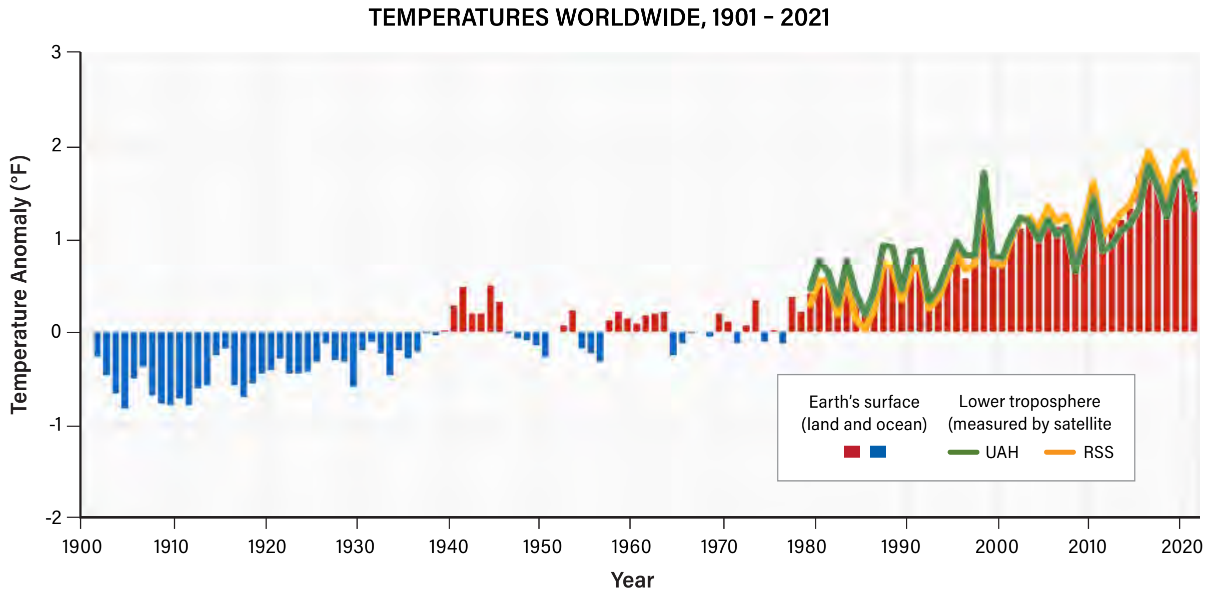


Figure 43. Temperature records.[171]

169. Constance Jenkins (NORAD/NORTHCOM Presentation to DSB).

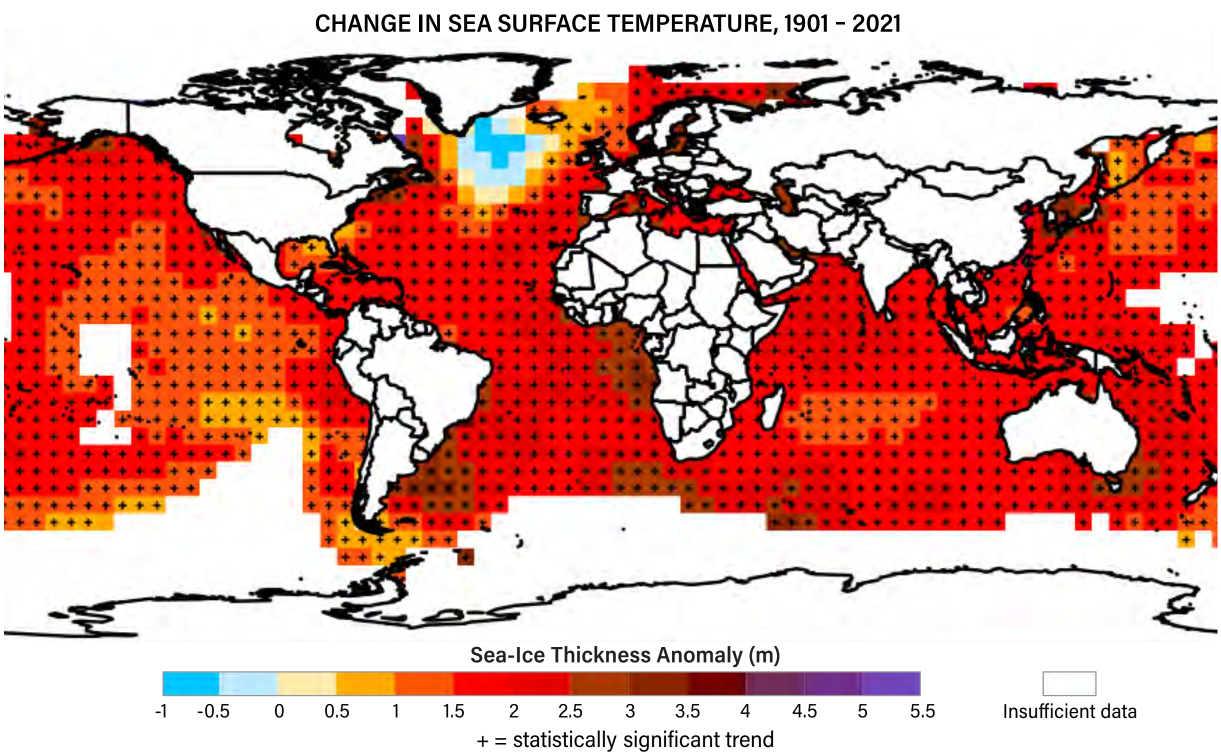
170. "Climate Change Indicators," EPA, last modified Dec. 13, 2023, https://www.epa.gov/climate-indicators/view-indicators.

171. Figure 43 Source: NOAA's National Centers for Environmental Information, https://www.ncei.noaa.gov/news/global-climate-202112.



Data source: NOAA (National Oceanic and Atmospheric Administration). 2022. Climate at a glance. Accessed March 2022. www.ncdc.noaa.gov/cag.
For more information, visit U.S. EPA's "Climate Change Indicators in the United States" at www.epa.gov/climate-indicators.

Figure 44. Temperature anomalies.

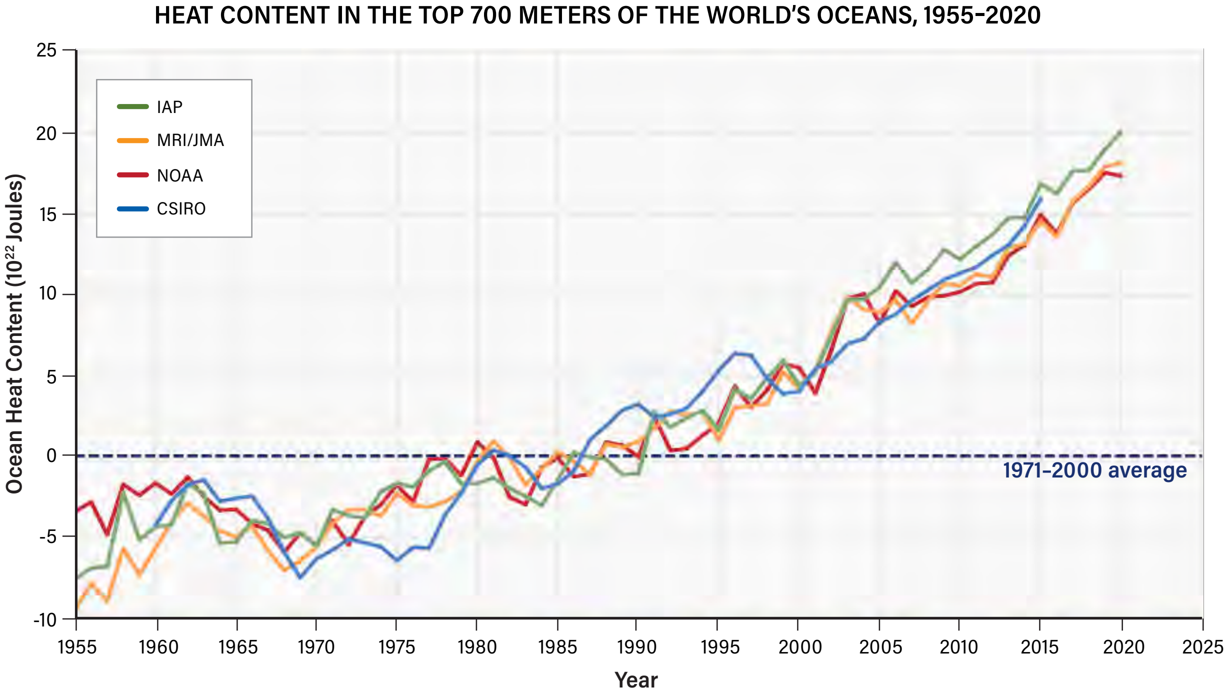


Data sources:

- IPCC (Intergovernmental Panel on Climate Change). 2013. Climate change 2013: The physical science basis. Working Group I contribution to the IPCC Fifth Assessment Report. Cambridge, United Kingdom: Cambridge University Press. www.ipcc.ch/report/ar5/wg1.
- NOAA (National Oceanic and Atmospheric Administration). 2021. NOAA Merged Land Ocean Global Surface Temperature Analysis (NOAAGlobalTemp). Accessed March 2021. www.ncdc.noaa.gov/data-access/marineocean-data/noaa-global-surface-temperature-noaaglobaltemp.

For more information, visit U.S. EPA's "Climate Change Indicators in the United States" at www.epa.gov/climate-indicators.

Figure 45. Sea surface temperatures.



Data sources:

- CSIRO (Commonwealth Scientific and Industrial Research Organization). 2016 update to data originally published in: Domingues, C.M., J.A. Church, N.J. White, P.J. Gleckler, S.E. Wijffels, P.M. Barker, and J.R. Dunn. 2008. Improved estimates of upper-ocean warming and multi-decadal sea-level rise. Nature 453:1090-1094. www.cmar.csiro.au/sealevel/thermal_expansion_ocean_heat_timeseries.html.
- IAP (Institute of Atmospheric Physics). 2021 update to data originally published in: Cheng, L., K.E. Trenberth, J. Fasullo, T. Goyer, J. Abraham, and J. Zhu. 2017. Improved estimates of ocean heat content from 1960 to 2015. Science Advances 3(3):e1601545.
- MRI/JMA (Meteorological Research Institute/Japan Meteorological Agency). 2021. Global ocean heat content. Accessed February 2021. www.data.jma.go.jp/gmd/kaiyou/english/ohc/ohc_global_en.html.
- NOAA (National Oceanic and Atmospheric Administration). 2021. Global ocean heat and salt content. Accessed February 2021. www.nodc.noaa.gov/OC5/3M_HEAT_CONTENT.

For more information, visit U.S. EPA's "Climate Change Indicators in the United States" at www.epa.gov/climate-indicators.

Figure 46. Ocean warming.

Major Gaps and Challenges – High Temperatures

High ambient temperatures often reduce optimum performance parameters. Rotary and fixed-wing aircraft will have greater takeoff and landing constraints along well understood temperature gradients. Higher inlet water temperatures reduce design efficiency for maritime heat exchangers, mostly affecting ship propulsion and secondary systems. This is true of nuclear and all other water injection powerplants, as well. The challenges associated with rising temperatures mean that the U.S. military and commercial entities must accept a reduction in design specifications for airborne, sea, and shore power plant operations or incorporate more robust designs.

Additionally, commercial equipment used on military platforms may be hindered by shortcomings in design due to extreme temperature variations, often not expected in commercially sourced subsystems. Unexpected failures and equipment lifetime reductions of electronic and mechanical systems will be challenged. Many systems relying on embedded Commercial Off The Shelf (COTS) components pose unknown risks to technical readiness, as assumptions about predicted environments may no longer be accurate through the operational service lifetimes of critical equipment.

Findings and Recommendations

Finding 6

Global DoD operations will occur in locations increasingly challenged by extreme weather and climate change conditions.

Recommendation 6.1

[Joint Staff (JS) J8, USD(A&S), USD(P), USACE] Continue to develop design factors for platforms and systems to operate in polar regions. Incorporate the design factors in future acquisitions to enable expanded polar operations. Near term (0-2 years).

[USSF, NGA] Update C5ISR polar requirements (include Space Development Agency and ODNI) to include emerging commercial space capabilities. Near term (0-2 years).

[USD(A&S), USD(P), Joint Staff] Further refine logistics and presence needs in the Arctic. Evaluate future maritime access requirements with North Atlantic Treaty Organization (NATO) Arctic Command and CCMDs, including increased frequency of Ice Exercise (ICEX) operations (currently every other year). Near term (0-2 years).

[USD(A&S), USD(R&E)] Expand development of coatings for naval/airborne platforms for ice mitigation. Leverage DARPA ICE program as applicable. Medium term (3-5 years).

Recommendation 6.2

[USD(A&S), U.S. Army Aviation, Naval Air Systems Command (NAVAIR), Air Force Research Laboratory (AFRL)/Air Force Materiel Command (AFMC)] Re-examine vertical lift (e.g., Future Vertical Lift (FVL)) and fixed wing performance. Generate specifications for electronic and mechanical components operating at "margin of safety" temperatures. Far term (5+ years).

[USD(A&S)/ Naval Sea Systems Command (NAVSEA)] Examine submarine, ship, ground, and air power and cooling requirements. Generate specifications for components operating at "margin of safety" temperatures. Far term (5+ years).

[USD(R&E)/NAVSEA] Leverage new biofouling coating technologies to address drag reduction (i.e., DARPA work in past and new programs in this area). Near term (0-2 years).

Polar Environments Example Solutions

ONR Arctic Mobile Observing System (AMOS)

The ONR AMOS program (Fig. 47) is an FY19-FY24 Innovative Naval Prototype (INP) program with the objective to develop and field a prototype robotic observing system to enable the persistent collection of Arctic environmental variables on, in, and below the sea ice.[172] Components include:

172. Tom Drake, "Climate Change and Global Security at the Office of Naval Research," (Presentation to DSB, SA Inc. Executive Conference Center, Arlington, VA, July 19, 2023).

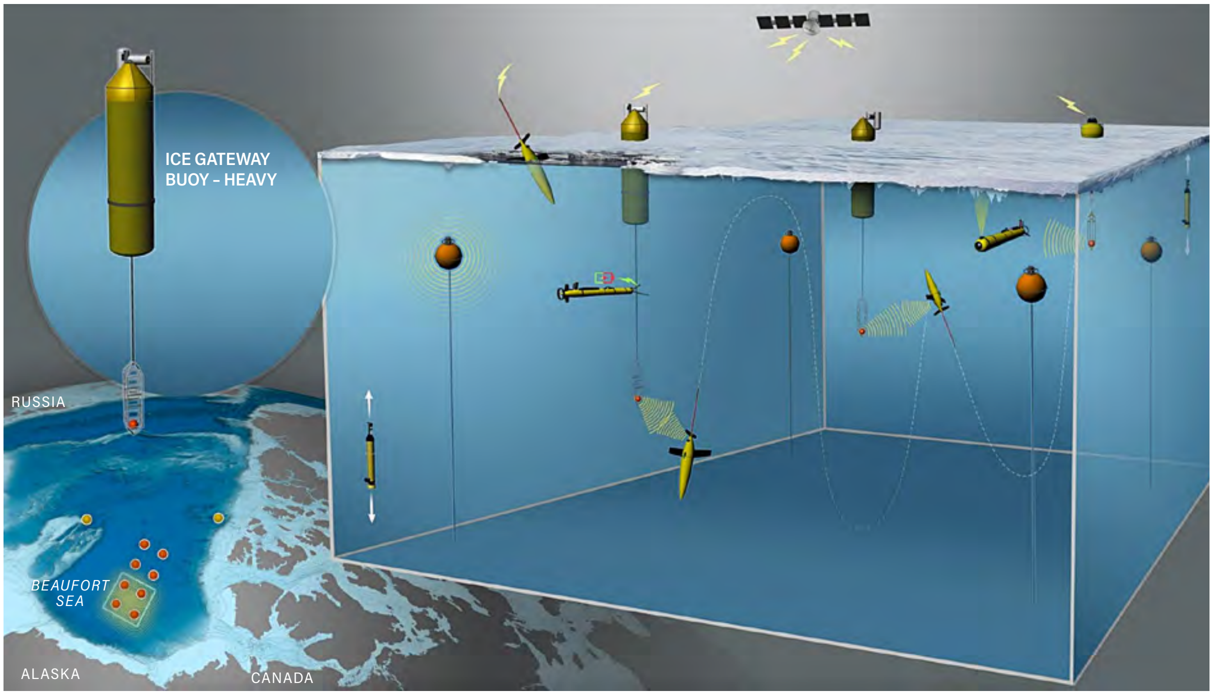


Figure 47. Sensors.[173]

- Mobile sensing systems for persistent Arctic observations – buoys, fast Unmanned Underwater Vessels (UUV), long-endurance gliders, and free-drifting profiling floats
- Under-ice acoustic navigation capability for UUVs (35Hz "underwater GPS" beacons)
- Bi-directional data transfer and mission adaptability

Over-the Horizon Radar (OTHR):

Northern Command/North American Aerospace Defense Command (NORTHCOM/NORAD) is currently working towards deploying 6th Gen (digitally beamformed) Over-the Horizon Radar (OTHR) systems to detect cruise missiles, hypersonic weapons, and Intelligence, Surveillance, and Reconnaissance (ISR) platforms approaching over the Arctic – the U.S. will deploy four systems; Canada will deploy another two systems. The first operational system is not expected to be fielded until 2028. The existing northern radar systems are fossil-fuel generator powered, which requires regular resupply – a complication in the Arctic; the opportunity to leverage microreactors as power sources for remote facilities is addressed elsewhere in this report.[174]

C5ISR

U.S. Space Force is deploying the Enhanced Polar System (EPS), consisting of two Extremely High Frequency (EHF) communications payloads hosted on satellites operating in highly elliptical orbits. Notably, the spacecraft are being developed and launched by Space Norway, the first-ever National

173. Figure 47 Source: Tom Drake, ONR Ocean Battlespace Sensing Dept., Presentation to DSB.

174. Constance Jenkins (NORAD/NORTHCOM Presentation to DSB).

Security Space payload to be hosted on an allied spacecraft.[175] Emerging commercial ISR and communications satellite constellations should also be evaluated for better polar coverage.

High-Temperature Environments Example Solutions

Electronics, Cooling, and Power Reduction

Given the reliance of military operations on C5ISR systems, high-performance electronic systems that can operate at higher temperatures and require less cooling are of paramount importance. Avionics and terrestrial applications, like the auto industry, will see increased needs for operating circuitry at higher temperatures, as well. One recently launched DARPA program in this area is High Operational Temperature Sensors (HOTS).[176] This program aims to develop new microelectronic sensor technologies capable of operations in high temperature environments.

As global temperature extremes increase upward, the potential for biofouling (the growth of organisms on the surfaces of vehicles and infrastructure) increases. The degradation of capabilities caused by biofouling include increased drag and fuel consumption on ships, increased corrosion, and contamination of critical infrastructure such as pipes, water and heat exchanger seawater inlets, and fouling of secondary systems such as cooling loops. These effects can go well beyond loss of mechanical function and extend into human health.[177] With increased variability in weather and climate comes a requirement for anti-fouling measures to address a diverse set of fouling organisms and processes.[178] Adding to the challenge, several antimicrobial paints and coatings implemented on ships and undersea vehicles to inhibit surface bacterial growth have been banned by the International Maritime Organization (IMO) due to their environmental toxicity.[179]

A large body of research continues to address the broad biofouling problem. Novel nanoengineered surfaces and coatings developed in collaborations between academia and the U.S. Army Construction Engineering Research Laboratory (CERL) and new biomaterial approaches led by DARPA offer some promise.[180] Specifically, a recently launched DARPA program is investigating new kinds of protective biofilms that may be able to mitigate micro biofouling created by bacteria and protozoa while remaining environmentally safe.[181] These efforts and their associated technologies are still nascent and require additional research and development to deliver the targeted effects that will help in increasingly variable ocean environments.

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175. "USSF's EPS-R Program on Schedule for Historic Polar Mission," United States Space Force, Dec. 8, 2021, https://www.spaceforce.mil/News/Article/2866035/ussfs-eps-r-program-on-schedule-for-historic-polar-mission/.

176. "New Sensors With the HOTS for Extreme Missions," DARPA, May 12, 2023, https://www.darpa.mil/news-events/2023-05-12.

177. J.W. Costerton, Philip S. Stewart, and E.P. Greenberg, "Bacterial Biofilms: A Common Cause of Persistent Infections," *Science* 284, 5418 (May 1999): 1318-1322, https://www.science.org/doi/10.1126/science.284.5418.1318.

178. Florian Weber and Naser Esmaeili, "Marine biofouling and the role of biocidal coatings in balancing environmental impacts," *Biofouling* 39, no. 6 (2023): 661-681, DOI: 10.1080/08927014.2023.2246906.

179. Aron Soerensen, "International Maritime Organization bans toxic paint substance cybutryne," BIMCO, June 18, 2021, https://www.bimco.org/news/environment-protection/20210618-imo-bans-toxic-paint-substance-cybutryne.

180. Julia H. Reed et al., "Ultrascalable Multifunctional Nanoengineered Copper and Aluminum for Antiadhesion and Bactericidal Applications," *ACS Applied Bio Materials* 2, no. 7 (May 2019): 2726-2737, https://pubs.acs.org/doi/10.1021/acsabm.8b00765.

181. "DARPA Selects Teams to Build Beneficial Biofilms," DARPA, March 21, 2023, https://www.darpa.mil/news-events/2023-03-21.

Humanitarian Assistance and Disaster Relief

State of the Science

The United States has a history of responding to HADR situations globally. Due to its significant lift capacity and global reach, the Department is often called upon to deliver immediate life-saving relief. Rapid airlift and sealift in regions where the existing infrastructure is damaged can shorten the humanitarian strife inherent in weather catastrophes. Also, military equipment is often suited for the environment of a catastrophe and can quickly be reconfigured following a HADR mission for normal tasking.

Extreme heat, more humidity, more moisture, and storms of greater intensity and frequency could result in successive humanitarian crises giving military forces responding to them limited time to recover between crises. Figure 48 below shows the possible implications of the U.S. military becoming involved in a HADR operation by the U.S. Indo-Pacific Command. The left-hand side of the chart shows trends that are being experienced in the theater. The right-hand side of the chart shows implications given those trends. The implications differ based on the speed of onset, i.e., storms and floods lead to rapid onset; slow-onset results from food and water insecurity and uncontrolled migration. The center of the figure shows the confidence levels of the trends given specific sub-regions within the theater. In this example, future projections point to an increased demand for HADR operations.

In addition to the potential for more frequent HADR crises, storms of greater intensity could also result in HADR missions of increasingly longer duration.

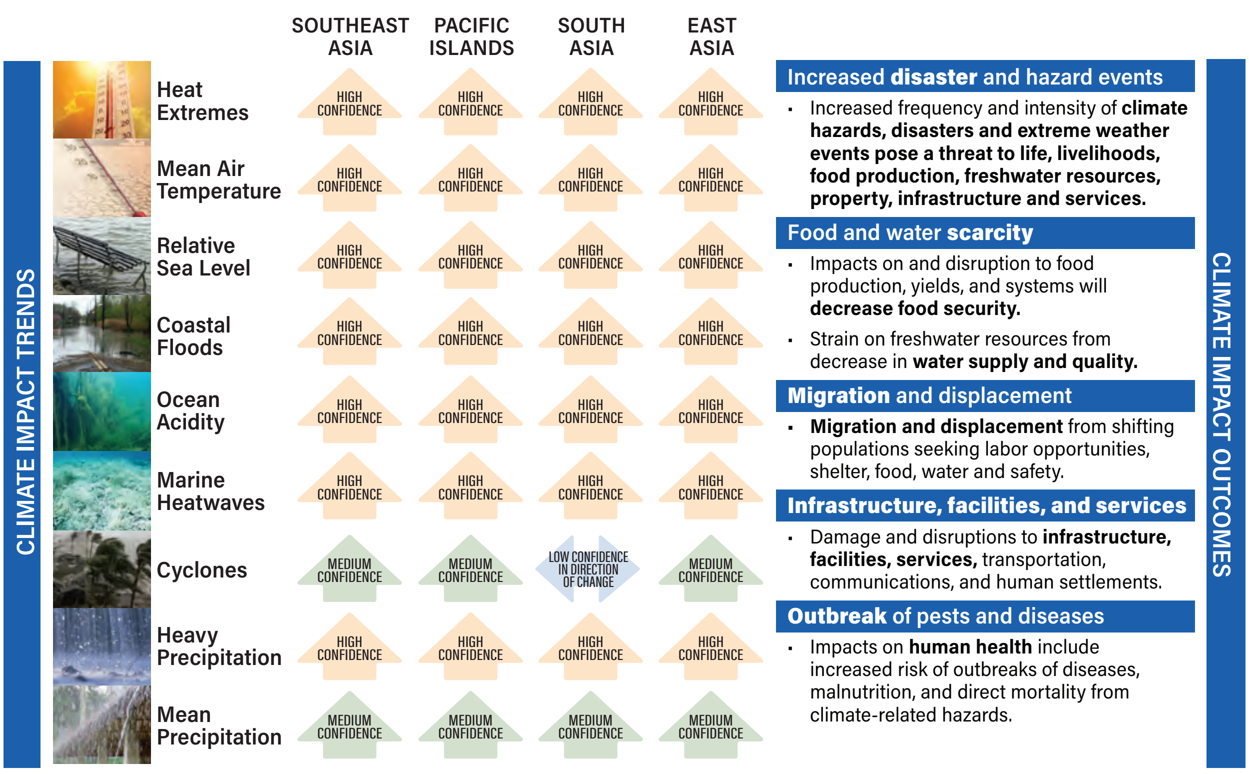

Figure 48. Impact trends.[182]

182. Figure 48 Source: Joe Martin, USINDOPACOM Climate Change Impact (CCI) Program, Presentation to DSB.

Major Gaps and Challenges

Even though the U.S. military has responded robustly and effectively to HADR crises in the past, the increased frequency of these crises, their nature, the potential for greater complexity and security challenges, may alter the demands on U.S. military forces. Their resources could be stretched thin given the need for training for potential conflicts on top of responding to HADR crises. Back-to-back HADR deployments with little time to recover and of longer duration puts pressure on deployment cycles, training, and refit.

Being able to predict the HADR demand is challenging. Scaling up resource requirements based on past deployments is helpful to a degree. However, the variability of climate change's effect on localized weather combined with an expectation that DoD operations will expand in new areas make any estimation of these operations wholly indeterminate.

Leveraging C5ISR capabilities to gain a complete picture of an HADR situation is helpful in the early understanding of emergency. Effective C5ISR, both unclassified for sharing with diverse entities and classified systems to fully flesh out a potential adversary's intent or to control disclosure of system capabilities, are essential to any DoD involvement in HADR operations. Joint Publication 3-29, Foreign Humanitarian Assistance, includes detailed processes to provide connectivity and collaboration using commercial networks and satellites. Amplification of these principles is essential as climate change broadens the probability for increased frequency and more complex HADR missions.

The inability to predict the frequency and complexity of future HADR operations, the decision-making calculus for increased demand for these operations, additional factors that come into play regarding when and where to involve the military, political positions going forward, and the very rationale for the U.S. military's involvement – make detailed planning for HADR operations nearly impossible. What can be done is to include HADR events in scenario planning and wargames. This gives practice to service members on the mechanisms involved with HADR and the uncertainty of decisions that might need to be made. The added advantage of scenario planning and wargames is the ability to involve potential partners, including Non-Governmental Organizations (NGO) and Allies. The circumstances of individual NGOs can change but the opportunity to develop strong relationships in advance of a crisis will be beneficial. Including these "players" will give service members a better understanding of the total force demand in HADR crises. Specific issues for consideration in scenario planning and wargames include:

- Force structure and platform requirements in support of more frequent and complex HADR in increasingly inhospitable locations, e.g., the Arctic and Sahel
- Addressing how the military can respond to HADR situations most effectively
- Theater Security Cooperation activities idealized for climate driven HADR crises.

Findings and Recommendations

Finding 7

Challenges posed by extreme weather conditions exacerbated by climate change will likely increase DoD Humanitarian Aid and Disaster Relief (HADR) operations.

Recommendation 7.1

[USD(R&E), Under Secretary of Defense for Intelligence and Security (USD(I&S)), CCMDs] Leverage next-generation C5ISR/platform capabilities for immediate in situ HADR missions. Near term (0-2 years).

Recommendation 7.2

[CCMDs, JS J5] Conduct scenario planning to better define requirements for increased frequency and complexity of future HADR operations. Medium term (3-5 years).

Recommendation 7.3

[Regional Combatant Commands] Integrate HADR in wargames, exercises, and related curriculums for climate-induced events. Medium term (3-5 years).

Humanitarian Aid and Disaster Relief Example Solutions

C5ISR

Widely implementing flexible interoperability and tunable levels of classification into next generation C5ISR systems for situations that require connection to DoD networks can help to streamline planning and response to HADR missions. Leveraging existing plans for frequency management and deploying mobile 5G networks in regions more likely to call for HADR operations can help to prioritize capabilities for these systems. This approach can also help to support operations that are able to share information.[183]

An example of next-generation capabilities for immediate in-situ HADR missions includes three ongoing DARPA programs: the Liberty Lifter, the Sea Train, and No Manning Required Ship (NOMARS). These DARPA efforts were developed to serve dual use application (canonical military CCMD missions and HADR). These programs/platforms provide examples of capabilities to enable force structure (with and without humans) that enable rapid logistics support at the scale to better support HADR operations.

Scenario Planning and Wargaming

An example of scenario planning to better define HADR requirements into wargames and exercises is

183. Joint Chiefs of Staff, *Foreign Humanitarian Assistance*, Joint Publication 3-29 (Joint Chiefs of Staff, 2019), IV-2, https://www.jcs.mil/Portals/36/Documents/Doctrine/pubs/jp3_29.pdf.

the INDOPACOM game of Ho'okele Mua that occurred in 2022.[184] The game was focused on creating the conditions in the Pacific theater in a future defined by expected climatic conditions. Another purpose was to help INDOPACOM incorporate climate change considerations more thoroughly into the command's planning process. Scenarios considered in the game were set in 2027, 2032, and 2037. Ho'okele Mua focused on 15 locations representing the types of situations INDOPACOM is likely to experience in the future.

The game yielded findings, such as:

- The consideration of the full range of climate change implications
- How to integrate climate considerations into decision-making processes for military operations (for example, articulating climate risk to military operations)
- Understanding the military's role in a crowded field of HADR responders.

One of the recommendations emerging from the game was that INDOPACOM would need to provide guidance on incorporating climate change variabilities into readiness. There is also a need for climate risk analysis tools tailored to military planning and operations, and reliable climate data specific to the region, topics which are addressed elsewhere in this report.

Section Summary

The U.S. military must be ready to project power, sustain operations, fight, and win in all domains and regions of the globe, each of which is being impacted differently by a rapidly changing climate.

In terms of human performance, heat-related illnesses, injury, and biohazards become more prevalent in climate change scenarios. Loss of training days due to high heat may become so pronounced that it compels the DoD to move its training commands northward. Polar operations warrant a litany of capabilities the DoD is without, or additional study is needed. Moreover, the requirements process in the DoD must now include more extreme operating conditions in future programs of record.

Many DoD facilities have some aspect of climate related conditions affecting their mission. Coastal and island infrastructures are especially under threat of more severe storms, wholesale flooding, and wind damage. Drought-stricken areas are also of particular concern because of increased habitation, worsening weather extremes, and uncontrolled wildfires. Also of high concern is risk to U.S. space launch infrastructure at Cape Canaveral and Vandenberg Space Force Base (SFB). Alternative space launch options are prudent in the event those sites are compromised. Hardening of the most vulnerable bases using traditional and novel technologies may help resiliency to climate change, while also considering alternative basing options may be needed. Future platforms and C5ISR systems must be designed for anticipated operating environment extremes, both in terms of higher temperatures in inland equatorial regions and higher ocean temperatures. Conversely, the logical expectation that the Department will assume a more Polar reach compels a corresponding effort to field equipment for the high latitudes. This will require leveraging climate modeling and decision support capabilities discussed in the earlier chapter within the acquisition process. Furthermore,

184. Joe Martin, "Ho'okele Mua: USINDOPACOM Climate Change Wargame 2022, Game Summary and Insights," (Presentation to DSB, SA Inc. Executive Conference Center, Arlington, VA, May 10, 2023).

climate-related changes in EM propagation in the troposphere, and undersea acoustic propagation, must be routinely monitored and well-understood to maintain C5ISR advantages.

Finally, climate-change related impacts are increasing the frequency and severity of natural disasters. It follows that these natural disasters on the global scale will sometimes warrant a DoD HADR mission. The DoD is encouraged to consider the likelihood of these operations in force design, development, and requirements. Again, advanced climate modeling and decision support capabilities should be leveraged in scenario planning and wargaming. Innovative logistics strategies and platforms should be developed to enable rapid response to such events, while reducing the demands on U.S. military assets and personnel. Commercial C5ISR capabilities must also be used to support such operations to relieve strain on DoD assets.

It is apparent that changes in the climate will change many facets of DoD force readiness, perhaps for decades to come. The DoD must prioritize comprehensive equipment and personnel adaptation measures to prepare for the diverse range of operating environments stretching from the rigid Arctic to Earth's sweltering midsection. From collaboration with international partners and other government agencies to individual equipping, DoD must be prepared for a comprehensive effort to operate regardless of conditions. Rapid deployment and pre-coordination with civilian agencies and international organizations will enhance the HADR mission if called upon. By proactively addressing these challenges, the Department can effectively fulfill its mission to safeguard national security and provide that worldwide deployability so vital in times of crisis.

Resource Scarcity and Supply Chain Vulnerability

Overview

Resource scarcity occurs when the demand for a natural resource exceeds its supply. This definition applies to a broad range of resources, from basic human needs such as water, food, and energy, to mined resources such as minerals crucial to energy generation and supply. This section focuses on water scarcity and its interplay with climate change and conflict. We also assess the status of the supply chain for minerals essential to the implementation of renewable energy technologies and national security objectives.

Resource Scarcity and Contested Access

State of Knowledge

Water security—sufficient access to water of adequate quality—is an essential precondition of human life and socioeconomic development. The availability of water also underpins food and energy security, as illustrated in Figure 49.

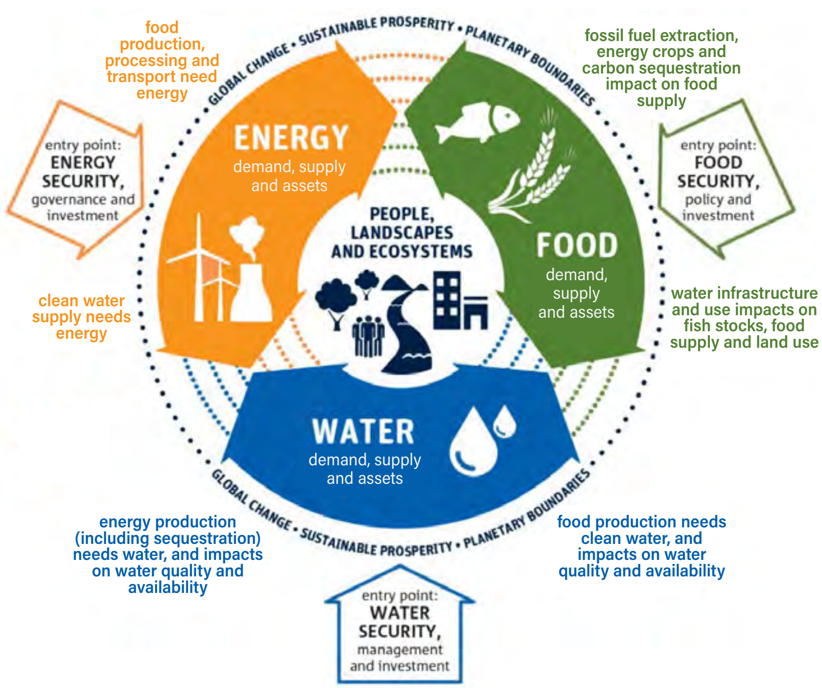

Figure 49. Sustainable development: the water-energy-food nexus.[185]

Although the proportion of the global population using safe drinking water services increased from 69% in 2015 to 73% in 2022, more than 2 billion people were still without

185. Figure 49 Source: IWA, 2018, https://www.iwa-network.org/wp-content/uploads/2018/05/sfs.jpg.

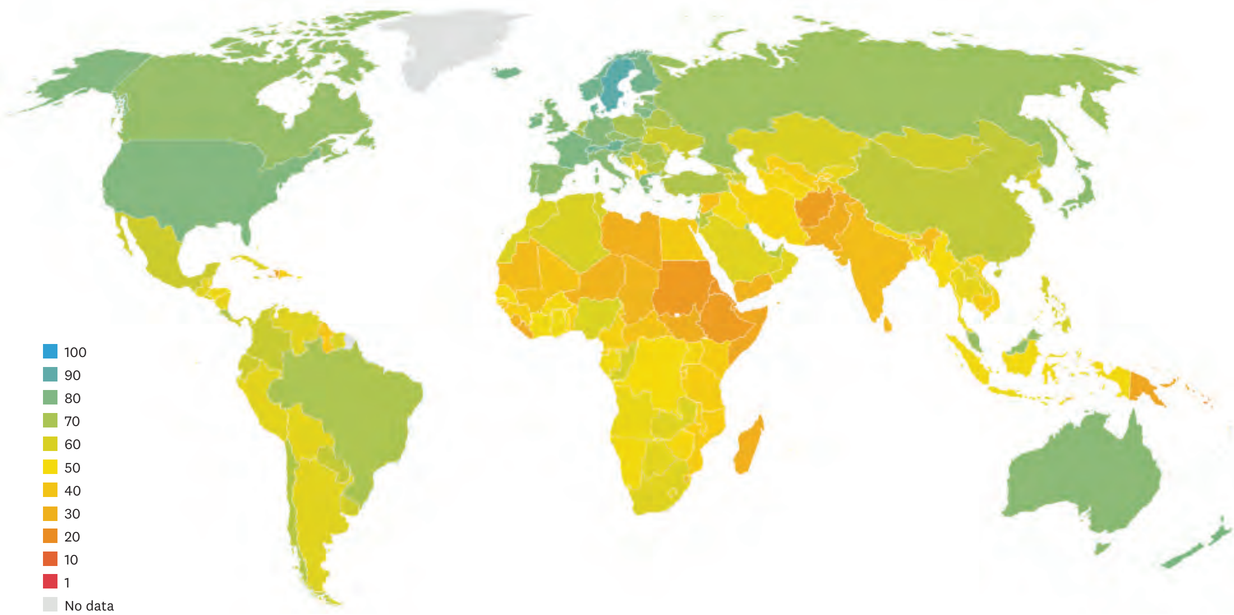

Figure 50. National water security mapped globally, based on a score of 1-100 (from least secure to most secure).[188]

potable water that year.[186] Figure 50 shows a global map of national water security assessed using the methodology developed by the United Nations University. The score ranges from 1 (the least secure) to 100 (the most secure).[187] The least water-secure regions are Africa, including the Sahel, the Horn of Africa, and parts of West Africa, in addition to South Asia and small island states.

Global water security is likely to worsen in the future. This is due to the combined effects of population growth (from 7.8 billion in 2023 to approximately 10 billion forecasted for 2050),[189] increasing demand for water from growing economies, the residual effects of repeatedly treating and retreating the same water source, pollution, and climate change, the latter impacting most strongly the regions that are already water insecure, as was discussed earlier in this report.

Too much water resulting from extreme weather events can be a problem as well. A recent United Nations publication points out that since the year 2000, flood-related disasters have risen 130% compared to the two previous decades.[190] An average of over 20 million people per year have been displaced internally by extreme weather events since 2008, with floods—fluvial (rivers), pluvial (known as flash floods), and coastal flooding—the most common causes of the displacement.[191]

186. *Sustainable Development Goals Report 2023: Special Edition*, (United Nations, 2023), 24, https://unstats.un.org/sdgs/report/2023/The-Sustainable-Development-Goals-Report-2023.pdf.

187. *Global Water Security 2023 Assessment*, (Hamilton, Canada: United Nations, University Institute for Water, Environment and Health, 2023), 8-9, https://reliefweb.int/report/world/global-water-security-2023-assessment.

188. Figure 50 Source: *Global Water Security 2023 Assessment.*

189. *World Population Prospects 2022*, (United Nations, Department of Economic and Social Affairs, Population Division, 2022), http://population.un.org/wpp/.

190. “Water – at the center of the climate crisis,” United Nations, https://www.un.org/en/climatechange/science/climate-issues/water.

191. *Forced from Home: Climate-Fueled Displacement*, (Oxfam, 2019), https://www.oxfam.org/en/research/forced-home-climate-fuelled-displacement.

Major Gaps and Challenges

According to the National Intelligence Council, water security problems during the next 20 years are likely to touch most elements of life, including political stability and interstate conflict.[192] Water scarcity can exacerbate existing social grievances and divisions and trigger destabilizing secondary effects, which can lead to conflict. In particular, water scarcity is becoming a tool in the operational strategy of belligerents.[193]

Historical records point to correlations between interstate conflict and water security. Economies challenged by water scarcity or lacking the ability to develop further without additional water sources have traditionally sought to expand their access to water.[194] Approximately 300 surface water basins and 600 shared aquifers cross international borders.[195] For many of these bodies of water, there are no water-use agreements between the neighboring states and no mechanisms for effective, coordinated management of the resource.

Understanding the relationship between water scarcity and conflict will become increasingly important to protecting U.S. interests and national security. The intersection of physical sciences (knowing where and when an extreme weather event may occur) and social sciences (knowing the potential societal/political impacts) requires further research in a DoD operational context. Physical science gaps call for the development of data driven, spatially explicit information on where resource scarcity exists now and where it will occur in the future. Social science can help fill gaps in the understanding of how state and non-state actors may leverage resource scarcity to gain advantage, and where this may occur due to pre-existing instabilities and/or other risk factors.

Ultimately, the DoD needs tools and data products, such as data-driven scenarios, models of socio-ecological systems, geospatial data from remote and ground sensors, and information regarding uncertainty in the data, to forecast the emergence of climate-driven events at relevant time and spatial scales and in the context of the socioeconomic settings. Decision-support tools that provide early warnings of resource scarcity will be essential to guide military planning and to ensure the most effective military response if needed.

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192. *Water Insecurity Threatening Global Economic Growth, Political Stability,* (National Intelligence Council's Strategic Futures Group, 2021), 7,

https://www.dni.gov/files/images/globalTrends/GT2040/NIC_2021-02489_Future_of_Water_18nov21_UNSOURCED.pdf.

193. Marcus King, *Weaponizing Water: Water Stress & Islamic Extremist Violence in Africa and the Middle East,* (Boulder, CO: Lynne Rienner Publishers, 2023).

194. Masahiro Murakami, *Managing water for peace in the Middle East: Alternative strategies* (Tokyo: United Nations University Press, 1995), https://collections.unu.edu/eserv/UNU:8713/Managing_water_Middle_East.pdf.

195. *Water Insecurity Threatening Global Economic Growth, Political Stability*, 8.

Findings and Recommendations

Finding 8

Resource scarcity and contested access to essential resources (e.g., food, water, energy) will contribute to more frequent and complex regional instability, conflict, and mass migration, particularly in regions with low adaptive capacity.

Recommendation 8.1

[Department of State (DOS), USAID, USD(R&E)/Minerva Program, USD(I&S), CIA] Establish a capability to combine activities and data analysis supporting climate change and social and economic stability/instability assessments. Near term (0-2 years).

Recommendation 8.2

[NGA] Leverage the growth in commercial remote sensing for monitoring migration, water/food scarcity, and critical resource extraction leading to potential conflict. Near term (0-2 years).

Recommendation 8.3

[DoD Climate Planning Cell, Services, USD(I&S), Defense Intelligence Agency (DIA)]: Integrate intelligence and CCMDs regional knowledge in areas vulnerable to food and water insecurity to inform sustainable preparation of forces and on-the-ground response in areas identified as climate-vulnerable. Medium term (3-5 years).

Resource Scarcity and Contested Access Example Solutions

An example of R&D investment that can lead to improved methodology for assessing the effect of resource scarcity and contested access is the Minerva Research Initiative administered by the Office of the Undersecretary of Defense for Research and Engineering. The goal of the initiative is to improve the DoD's basic understanding of the social, cultural, behavioral, and political forces that shape regions of the world of strategic importance to the U.S. All supported projects are university-based and unclassified, with the intention that all work be shared widely. Several recently awarded research projects (e.g., Social Impact of Climate Change (2021); Climate Change and Great Power Competition (2021); Climate Change and Alternative Governance (2021); etc.) help to answer key questions related to global security, e.g., how different actors contribute to or impede climate governance (from long-term challenges to crisis response) or how climate change affects conflict or collaboration between great powers.

The PREPARES program builds on Minerva to forecast local and regional climate-change effects, assess and predict societal impacts and responses, and provide operational planners technically relevant and operationally precise scenarios to incorporate into their plans. Example thrusts include assessments of the ability of state and non-state groups to organize, mobilize, and gain advantage in the face of climate-exacerbated resource scarcity and the locations where this may occur due to pre-existing instabilities and/or other risk factors.

The DoD's understanding of theaters in which the U.S. military already operates or which it may

Figure 51. SAR image obtained by Sentinel-1 Satellite, showing receding flood waters in a region of Honduras affected by Hurricane Iota in November of 2020.[196]

need to enter can be improved by the information extracted from satellite images produced by multispectral optical and SAR sensors. Figure 51 shows an example SAR image of a region of Honduras in Central America, which flooded after Hurricane Iota in November of 2020.

NGA's Commercial Initiative to Buy Operationally Responsive Geospatial Intelligence (CIBORG) initiative will enable centralized, standardized, contractual access to emerging commercially available imagery, data, analytical capabilities, and services for military users. For example, PlanetScope, the constellation of satellites operated by Planet Labs, can provide unclassified optical images of the Earth's surface with 3.7 m resolution.[197] The daily revisits for most locations offer the opportunity to monitor changes in physical features and geographically referenced activities on the ground, delivering timely insights as events unfold.

Artificial intelligence and machine learning have revolutionized computer vision, freeing human analysts for higher-level complex tasks. Computers can interpret high-resolution images to detect and classify specific objects, search for objects in large geographic areas, monitor the areas, and map the features of interest. Recognizing the progress in commercially available advanced analytics platforms, NGA announced in January of 2024 the call for proposals for *Luno A*, a $290 million contract to acquire unclassified commercial Geospatial Intelligence (GEOINT)-derived computer vision and analytic service capabilities.[198] Climate security and natural resources, coupled with change detection, are one of the main areas of interest. The unclassified nature of commercial data will ensure that *Luno A* products, data, and/or services are easily shareable with like-minded partners and allies across the globe.

Using data from remote sensing as well as on-the-ground intelligence, CCMDs should begin or accelerate collecting data on how the changing climate is affecting their respective theaters. This

196. Figure 51 Source: NGA.

197. Planet Labs. https://www.planet.com/products/planet-imagery/.

198. "NGA announces $290M Luno A commercial data RFP," NGA, Jan. 11, 2024, https://www.nga.mil/news/NGA_announces_$290M_Luno_A_commercial_data_RFP.html.

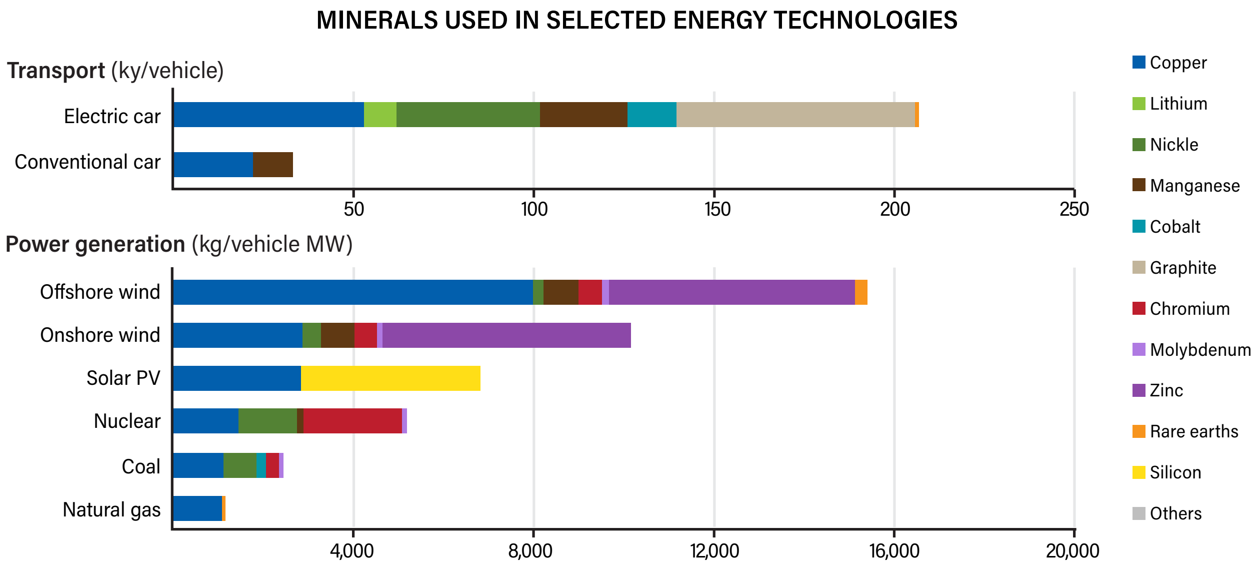

Figure 52. Minerals used in selected energy technologies. Note that electric car requires 6x material inputs than conventional car.[199]

data will be important to establish a baseline to assess not only current conditions but also the rate of change. CCMDs can then use this information to update operational plans, focusing on areas where existing water insecurity may be used by belligerents to revive historical animosities, leading to conflict.

Supply Chain Vulnerability: Critical Minerals

State of Knowledge

In the context of climate change, the phrase "critical minerals" typically denotes those naturally occurring compounds that are essential to renewable energy technologies. The DoD defines strategic and critical minerals as those that support military and essential civilian industry; and are not found or produced in the United States in quantities to meet our needs.[200] Solar and wind technologies, coupled with expanded electrical grids, are seen as key enablers of the reimagining of energy generation systems. Other technologies such as hydrogen, sustainable aviation fuels, nuclear energy, carbon capture and sequestration, and even fusion energy in the future are also seen as important to the energy transition. Rapid deployment of many of these technologies implies a significant increase in demand for minerals such as lithium, nickel, cobalt, manganese, and graphite (critical for batteries), rare earth elements (essential for permanent magnets for wind turbines and electric-vehicle motors), silicon (for solar panels), and copper (the cornerstone of electricity networks), see Figure 52.

199. Figure 52 Source: *The Role of Critical Minerals in Clean Energy Transitions*, (Paris, France: IEA, 2022), 26, https://iea.blob.core.windows.net/assets/ffd2a83b-8c30-4e9d-980a-52b6d9a86fdc/TheRoleofCriticalMineralsinCleanEnergyTransitions.pdf.

200. "Executive Order on America's Supply Chains," The White House, Feb. 24, 2021, https://www.whitehouse.gov/briefing-room/presidential-actions/2021/02/24/executive-order-on-americas-supply-chains/.

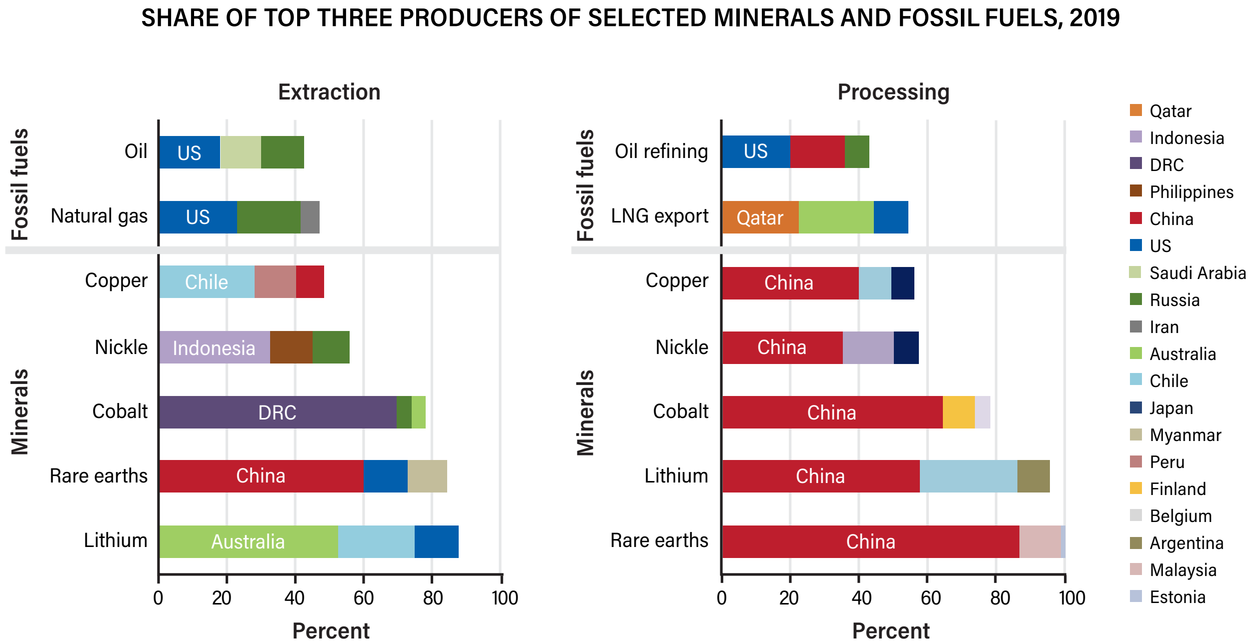

Figure 53. The share of top three producers of selected minerals in 2019.[201]

Major Gaps and Challenges

To achieve net-zero GHG emission targets globally by 2050 will require over 30 million tons of mineral inputs, 3.5 times more in 2030 than are produced today.[202] Materials used for batteries, such as lithium, graphite, cobalt, and nickel, are the drivers of demand growth, as is copper, an integral part of electric grids. According to the International Energy Agency (IEA), 80 million kilometers of transmission lines will need to be added or replaced by 2040 for countries to meet their current climate goals.[203]

The major challenge for the U.S. and its Allies is the geographical concentration of the production of critical materials (Figure 53). In particular, China has gained access to a wealth of critical minerals, such as cobalt, copper, and rare earth elements, through significant investments in mining operations across the continent. Chinese companies have established a dominant position in the Democratic Republic of Congo, which holds a substantial portion of the world's known cobalt reserves. As discussed earlier in this report, these investments often come with infrastructure development projects, like roads and ports, further entrenching China's economic influence in the region. Additionally, China engages in long-term contractual agreements and the development of facilities for processing of the raw minerals, critical to controlling the supply chain.

To mitigate these supply chain risks, the DoD and international partners must diversify their sources of critical minerals, invest in alternative materials and technologies, and strengthen international

201. Figure 53 Source: *The Role of Critical Minerals in Clean Energy Transitions,* 13.

202. "Critical Minerals Data Explorer," IEA, last modified July 11, 2023, https://www.iea.org/data-and-statistics/data-tools/critical-minerals-data-explorer.

203. Electricity Grids and Secure Energy Transitions, (Paris, France: IEA, 2023), 7, https://www.iea.org/reports/electricity-grids-and-secure-energy-transitions.

cooperation to ensure a more secure and sustainable supply chain. Additionally, as part of the whole-of-government effort, the U.S. promoting responsible mining practices and environmental stewardship in extracting these resources is crucial to minimizing negative impacts on the climate.

Defense Logistics Agency (DLA) Strategic Materials is the leading agency for the study, planning, management, and procurement of materials crucial to the U.S. defense industry. The agency's technical expertise and global supply analysts recommend various strategic materials/commodities that are stored in various locations within the U.S. This national stockpile is a physical reserve of definite quantities of approximately forty specific materials owned by the U.S. and stored in government facilities. The direction for this program is the Strategic and Critical Materials Stock Piling Act (50 U.S.C.), which is frequently updated to reflect technical trends of manufacturing, supply, and obsolescence. This agency's effort is especially important in providing a higher level of assurance that critical materials will be available in a viable quantity if worldwide supply is interrupted.

The climate system itself can worsen vulnerabilities of the supply chain. Approximately half of global lithium and copper production is concentrated in areas of water scarcity, especially along the coasts of Chile, Peru, and Mexico.[204] Large amounts of critical materials are mined in areas of Africa that are expected to be impacted by rising temperatures, see Figure 54. Many of the areas important in raw commodity production are also beset with internal strife and political instability, exacerbated by strained environmental conditions. External business interests and foreign influence operations compound the complexity and instability of the supply chain. For example, the Mediterranean basin and the Sahel region in Africa are areas of special interest for foreign influence operations.[205]

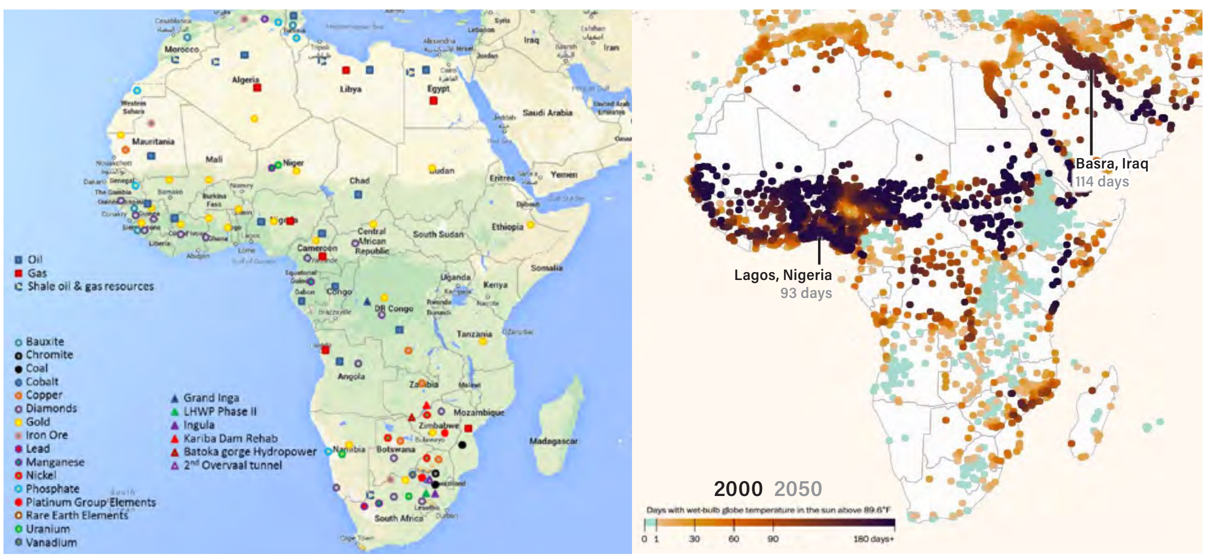

Figure 54. (Left) Map of Africa with locations of mines for critical materials; (Right) Map of Africa with locations where people are expected to experience dangerous heat in 2050.[206]

204. *The Role of Critical Minerals in Clean Energy Transitions*, 40.

205. Paul Stronski, "Russia's Growing Footprint in Africa's Sahel Region," Carnegie Endowment for International Peace, Feb. 28, 2023, https://carnegieendowment.org/research/2023/02/russias-growing-footprint-in-africas-sahel-region?lang=en.

206. Figure 54 Sources: Left Map - Southern African Institute of Mining and Metallurgy (SAIMM); Right Map: The Washington Post, https://www.washingtonpost.com/climate-environment/interactive/2023/extreme-heat-wet-bulb-globe-temperature/.

Findings and Recommendations

Finding 9

Climate pressures will further strain supply chains, including minerals and rare earths critical to DoD operations and missions often found in areas controlled or influenced by adversaries. This will necessitate new approaches and increased monitoring to anticipate surprise.

Recommendation 9.1

[USD(R&E), USD(A&S)] Analyze gaps on critical, climate-induced vulnerabilities to supply chains and plan for securing access to critical minerals as a part of mission objectives. Near term (0-2 years).

[DLA] Increase the stockpile of rare earth and critical minerals, with a stated preference for domestically mined and/or processed materials. Medium term (3-5 years).

Recommendation 9.2

[ODNI] Working with the commercial sector, leverage open source and classified intelligence and sensing to provide current information on emerging supply chain vulnerabilities due to climate threats. Near term (0-2 years).

Recommendation 9.3

[USD(A&S), USD(R&E)] Coordinate with DOE on R&D investments for the efficient and sustainable provision of rare earth and critical minerals to ensure mission objectives, including development of substitutes and re-use and re-cycling strategies. Medium term (3-5 years).

Supply Chain Example Solutions

The issue of critical materials is not new, and a variety of U.S. organizations have been making extensive assessments in this area for many years. For example, the U.S. Geological Survey's (USGS) *Critical Mineral List,* published in 2021, evaluated the criticality of minerals during 2018-2021 based on economic vulnerability and potential for disruption.[207] The U.S. DOE released a *Critical Materials Assessment Draft Report* in May 2023.[208] The DOE report naturally focused on those materials critical for energy applications, considering the distinct categories of applications and changes in market developments and the supply chain. A similar, DoD-focused periodic assessment might also be helpful in highlighting strategic solutions to the critical materials supply chain vulnerabilities, to include refinement and processing for manufacturing that may be single supply chain vulnerabilities for DoD-related industries.

In its *Critical Materials Rare Earths Supply Chain: A Situational White Paper*, the DOE suggested that three coordinated primary approaches, or pillars, might be effective in addressing supply chain

207. Nedal T. Nassar and Steven M. Fortier, *Methodology and technical input for the 2021 review and revision of the US Critical Minerals List,* Open-File Report 2021–1045, (US Geological Survey, 2021), https://doi.org/10.3133/ ofr20211045.

208. *Critical Materials Assessment,* (US Department of Energy, 2023), https://www.energy.gov/sites/default/files/2023-05/2023-critical-materials-assessment.pdf.

issues.[209] These are listed here (almost verbatim) because of the scope of activities and investments that they cover:

1. Diversifying the supply of critical materials, including increasing domestic production, separations, and processing
2. Developing substitutes
3. Driving recycling, reuse, and more efficient use of critical materials.

The broad scope of possible solutions suggests different, parallel investments. Scientific and technological innovation always offers important leverage. Partnerships with different government agencies and the commercial sector are important in taking ideas to implementation, bolstered by policy incentives.

A recent example of R&D investments targeting the provision of critical minerals is the Critical Materials Innovation Hub (CMI), established in 2013 and led by Ames National Laboratory. As suggested in the previous discussion, the effectiveness of the CMI depends on its ability to develop solutions *across* the materials' life cycle and on the richness of its multi-disciplinarity. In addition to benefits for the environment and reduction of waste, such solutions can reduce the impact of supply chain disruptions and price fluctuations associated with these valuable resources. The CMI addresses challenges in critical materials across a broad spectrum, which includes mineral processing, manufacture, substitution, efficient use, and circular economy; such an integrated approach is essential to creating a sustainable and holistic solution to challenges in supplying critical materials for the nation. CMI includes expertise from four national laboratories, over a dozen universities, and over thirty industry partners to minimize materials criticality as an impediment to the commercialization of clean energy technologies.

To complement the investments and resources of the CMI, the DOE Advanced Materials and Manufacturing Technologies Office (AMMTO) recently issued a Funding Opportunity Announcement (FOA), investing $10 million to bridge the gap between applied R&D and large-scale demonstration/manufacturing efforts.[210]

Within the DoD, DARPA is exploring biogenic means of mining and purifying rare earth elements (REEs) through its Environmental Microbes as a BioEngineering Resource (EMBER).[211] Three teams have been selected: the intention is to apply synthetic biology methods to engineer organisms and/or biomolecules to enable the specific binding of REEs under harsh conditions, then integrate these technologies into a functioning biomining workflow for purifying individual REEs. In addition, DARPA's program on Recycling at the Point of Disposal (RPOD) will evaluate the technical feasibility of recovering multiple low-volume fraction critical elements present in end-of-life electronics hardware, or otherwise called, e-waste.[212]

209. *Critical Materials Rare Earths Supply Chain: A Situational White Paper*, (US Department of Energy, 2020), 2, https://www.energy.gov/sites/default/files/2020/04/f73/Critical%20Materials%20Supply%20Chain%20White%20Paper%20April%202020.pdf.

210. "DOE Launches Critical Materials Collaborative to Harness and Unify Critical Materials Research Across America's Innovation Ecosystem," Office of Energy Efficiency & Renewable Energy, Sept. 21, 2023, www.energy.gov/eere/articles/doe-launches-critical-materials-collaborative-harness-and-unify-critical-materials.

211. "DARPA Names Teams to Develop Biotechnologies to Purify Critical Elements," DARPA, Oct. 6, 2022, https://www.darpa.mil/news-events/2022-10-06a.

212. "Recovering Rare-Earth Elements from E-Waste," DARPA, June 10, 2022, https://www.darpa.mil/news-events/2022-06-10.

Also of interest are new critical mineral finds in the U.S. For example, as described in recent Congressional testimony, "the 3PL mining claims (in Nevada) comprise a 2000-foot-deep brine pool, consisting of globally significant concentrations of valuable, recoverable critical and rare earth minerals, such as lithium and boron."[213] The project in fact would triple the U.S. Lithium resources overnight, but as recently as May of 2023 both NASA and the Bureau of the Interior had blocked efforts to mine the resources in the area.[214] Given the critical nature of these minerals to the U.S. economy in general and to the DoD in particular, it will be important to find ways to permit not only the mining but also processing of the minerals to augment DLA's stockpile.

Section Summary

Climate change is expected to exacerbate water scarcity that already affects 2 billion people worldwide. Conversely, more intensive storms will worsen flooding in low-lying areas of the tropics and coastal regions worldwide. Extreme weather events can have the greatest impact in regions with low adaptive capability, amplifying the potential for political and economic instability. Understanding the relationship between resource scarcity and conflict will become increasingly important to protecting U.S. interests and national security in the affected theaters. We recommend continued development of decision support tools that can provide early warning of resource scarcity at the time and spatial scales relevant to military planning and socioeconomic models that can alert to increased potential for intra- and interstate conflict. To support the model development and to develop adaptive engagement opportunities, CCMDs should collect data on how the changing climate affects their respective theaters and adapt engagement opportunities accordingly. The integration of model outputs with other intelligence will inform the preparation of forces and on-the-ground response to the conflict in climate-vulnerable regions.

The energy transition—the reimagining of national and global energy generation systems on the path to net-zero GHG emissions targets—has created increasing demand for minerals that are essential to the production of batteries and expansion of electric grids. The mining and processing of these materials is geographically concentrated, making the supply chain sensitive to trade restrictions, regulatory changes, and political instability in a small number of countries. Furthermore, many of the mines are in regions of Africa that are expected to be particularly impacted by rising temperatures. In addition to traditional countermeasures such as stockpiling, we recommend that DoD coordinates with DOE on R&D investments for the sustainable provision of critical minerals, including the development of substitutes and recycling strategies.

213. *Testimony regarding withdrawal of land in Railroad Valley, Nevada from disposition under the United States mineral leasing laws*, Subcommittee on Energy and Mineral Resources House Committee on Natural Resources, United States House of Representatives (2023) (statement of Kevin Moore, Chairman and Chief Financial Officer, 3 Proton Lithium, Inc.), 1, https://naturalresources.house.gov/uploadedfiles/testimony_moore.pdf.

214. "3PL: Interior, NASA Block Full Development of Largest Lithium Deposit in North America," PR Newswire, May 2, 2023, https://www.prnewswire.com/news-releases/3pl-interior-nasa-block-full-development-of-largest-lithium-deposit-in-north-america-301813490.html.

Diplomacy and Opportunities in Adversity

Overview

Climate change has altered the landscape of international affairs. From its effect on infrastructure and people's access to commercial resources, to reshaping geopolitical dynamics, a rapidly changing climate increasingly influences access to essential resources for large populations. The DoD must understand these myriad conditions to accurately develop regional security projections.

As a driver of potential realignment in global relationships, climate change is a threat multiplier, acting both as an independent variable, since no short-term solution exists to stop it from occurring, and as a dependent pivotal variable, as it relates to trends in international affairs. Its effects vary as to how rapidly changing weather patterns influence a particular region, the availability of critical minerals and resources to drive the transformation towards a net-zero-carbon economy, the availability of national wealth to combat climate ill-effects, the attention a particular area garners from other nations or business interests, and whether climate unearths new or legacy strife within a population. These multifaceted effects manifest in numerous ways, such as increased electricity demand for cooling or the geopolitical tensions arising from the management of water resources. This context sets the stage for the DoD to be engaged in climate diplomacy and seize opportunities to enhance global stability and security.

This section discusses how the Department of Defense must collaborate with allies, utilize U.S. relationships and partnerships globally, and work with potential adversaries to proactively manage and mitigate global tensions arising from climate change. Areas least capable of adapting to climate effects, like the Sahel, are often those most at risk, while regions previously unchallenged, such as the Arctic, may become conflict prone.

Background

The Department of Defense has the international relationships, the worldwide posture, and an array of like-minded Allies to play a significant role in addressing the effects of climate change. A broad consortium of nations has collaborated on mitigation and adaptation strategies to better prepare for more pronounced climate change effects.[215] This places the DoD in a pivotal position to guide and enhance these efforts. The DoD can foster those partnerships in regions facing heightened security related issues by collaborating with allies to help mitigate climate-induced risks. Moreover, the Department can better protect its worldwide national security infrastructure and force posture

215. "EU unveils sweeping climate change plan," BBC, July 14, 2021, https://www.bbc.com/news/world-europe-57833807.

by assisting partners to better mitigate the debilitating aspects of rising global temperatures. Additionally, through its extensive global presence and logistical capabilities, the DoD can offer crucial support in disaster response and recovery operations, easing humanitarian aid delivery worldwide.

The Arctic Region: In the Arctic, where rapid ice melt is paving the way for new shipping routes, potentials for resource extraction, and increased geopolitical competition, the DoD has been promoting cooperation among Arctic nations through initiatives like the NATO Climate Change and Security Action Plan (c. 2021).[216] The DoD is also committed to ensuring the responsible stewardship of the region's fragile ecosystems in its operations.

The Sahel, South Asia, and Low-Lying Island Nations: Contrastingly, regions such as the Sahel, South Asia, and low-lying island nations in the Indian and Pacific Oceans face escalating threats from extreme weather events in both frequency and severity. These diverse regions are increasingly prone to greatly fluctuating precipitation, causing extended droughts to vicious storms and heightened typhoon activity, combined with subsidence and encroaching sea-level rise. The DoD can leverage its partnerships, share technical expertise, train host nation forces, and support mechanisms to enhance local resilience efforts. This support could extend not only to DoD facilities but also bolster the supporting communities' capacity to adapt to and overcome climate-related challenges.

State of Affairs

The Board recognizes the critical need for multilateral cooperation among the DoD and its Allies and partners to address climate-related security challenges. Central to these efforts are comprehensive partnerships which share information, conduct joint planning, and coordinate respective responses to all aspects of climate-related adaptations.

Strategic Collaborations and Initiatives: In the Arctic, the U.S. and NATO are actively addressing the intricate relationship between climate change and national security through a mix of military, diplomatic, and environmental measures. These efforts are critical for the stability and resilience of the region. The Arctic Council has emerged as a key platform for these combined efforts, recognizing the Arctic's growing global significance.[217] Initiatives like the Green Defense Framework of 2014,[218] which focuses on sustainability in military operations, and NATO's annual Climate Change and Security Impact Assessments,[219] highlight the proactive steps taken. These efforts are supported by adapting to green technologies and promoting consistency in operational standards through Standardization Agreements (STANAGs), enhancing interoperability across different regions under the Climate Change and Security Action Plan.[220]

Disaster Response and Support: While disaster response is not a primary mission for the DoD, the Department's role in supporting civil authorities during extreme weather events is increasingly crucial. An example of enhancing disaster preparedness is the Partners in the Blue Pacific (PBP)

216. *NATO Climate Change and Security Action Plan*, (NATO, 2021), https://www.nato.int/nato_static_fl2014/assets/pdf/2023/7/pdf/230710-climate-change-best-practices.pdf.

217. "About the Arctic Council," https://arctic-council.org/about/.

218. Kristian Knus Larsen, *The NATO Green Defence Framework, in: Unfolding Green Defense*, (Centre for Military Studies, 2015), https://www.jstor.org/stable/pdf/resrep05270.5.pdf.

219. *NATO Climate Change and Security Impact Assessment, Second Edition 2023*, (NATO, 2023), https://www.nato.int/nato_static_fl2014/assets/pdf/2023/7/pdf/230711-climate-security-impact.pdf.

220. "NATO Climate Change and Security Action Plan," NATO, June 14, 2021, https://www.nato.int/cps/en/natohq/official_texts_185174.htm.

program, which, although not a DoD initiative, has implications for improving DoD infrastructure in the Pacific Island atolls.[221] This aspect underscores the DoD's vital role in logistical support and life-saving missions during crises.

Localized Adaptation Strategies: Recognizing the need for region-specific adaptation strategies is crucial, especially in conflict-prone areas like the Sahel. Here, environmental degradation exacerbates security challenges, necessitating integrated approaches to manage environmental and social vulnerabilities. This may include supporting local infrastructure resilience, collaborating with private industry for robust power grids, promoting sustainable resource management, and enhancing early warning systems for natural disasters and resource conflicts.

Regional Cooperation and International Dialogues: In the Indo-Pacific, the Quad (Quadrilateral Security Dialogue), including Japan, India, Australia, and the U.S., initially focused on security, has expanded to include climate and commercial considerations.[222] Initiatives like the Climate Information Services Task Force and Infrastructure Fellowship Program under the Quad are pivotal in building sustainable infrastructure and managing resources in at-risk areas. The Indo-Pacific Partnership for Maritime Domain Awareness, another Quad initiative, aims to combat illegal fishing, contributing to resource conservation.

Interagency and International Collaborations: Nation-to-nation collaboration on climate issues is an expanding facet of international diplomacy. For instance, the U.S.-India Climate and Clean Energy Agenda 2030 Partnership coordinates efforts to reduce greenhouse gas emissions and promote clean energy.[223] The U.S. Agency for International Development (USAID) Climate Strategy 2022-2030 is another vital interagency effort, assisting nations in balancing sustainable climate actions with emissions reduction.[224] Additionally, the Major Economies Forum on Energy and Climate (MEF), initiated in 2023, builds on the Paris Climate Agreement to promote ambitious climate action and international cooperation on energy and climate issues.[225] This forum serves as a high-level platform for consensus building and advancing global climate goals in international arenas like the United Nations Framework Convention on Climate Change (UNFCCC) negotiations.[226]

Major Gaps and Challenges

The Board recognizes that significant gaps and challenges still need to be addressed to effectively manage interconnected climate impacts that could be a leading element in future conflicts.

221. "Statement by Australia, Japan, New Zealand, the United Kingdom, and the United States on the Establishment of the Partners in the Blue Pacific (PBP)," The White House, June 24, 2022, https://www.whitehouse.gov/briefing-room/statements-releases/2022/06/24/statement-by-australia-japan-new-zealand-the-united-kingdom-and-the-united-states-on-the-establishment-of-the-partners-in-the-blue-pacific-pbp/.

222. "Quad Leaders' Joint Statement: 'The Spirit of the Quad'" The White House, March 12, 2021, https://www.whitehouse.gov/briefing-room/statements-releases/2021/03/12/quad-leaders-joint-statement-the-spirit-of-the-quad/.

223. "U.S.-India Joint Statement on Launching the 'U.S.-India Climate and Clean Energy Agenda 2030 Partnership,'" U.S. Department of State, April 22, 2021, https://www.state.gov/u-s-india-joint-statement-on-launching-the-u-s-india-climate-and-clean-energy-agenda-2030-partnership/.

224. "USAID Climate Strategy 2022–2030," USAID, April 21, 2022, https://www.usaid.gov/policy/climate-strategy.

225. "Chair's Summary of the Major Economies Forum on Energy and Climate Held by President Joe Biden," The White House, April 21, 2023, https://www.whitehouse.gov/briefing-room/statements-releases/2023/04/21/chairs-summary-of-the-major-economies-forum-on-energy-and-climate-held-by-president-joe-biden-2/.

226. "What is the United Nations Framework Convention on Climate Change?" United Nations Climate Change, https://unfccc.int/process-and-meetings/what-is-the-united-nations-framework-convention-on-climate-change.

Strategic Preparedness and Response Planning: A major gap is the lack of strategic foresight, planning, and training to address climate-related challenges, such as food and water scarcity, population displacement, coastal flooding, and resource competition, which are common precursors to instability. National, regional, and theater security plans specifically tailored to address the unique challenges posed by climate change are insufficient. These plans are vital for preparing host nations for the destabilizing effects of localized climate changes and for enhancing disaster response capabilities. Furthermore, at-risk nations and regions are often ill-equipped with the necessary training, education, and planning tools that would enable them to effectively manage and recover from disasters. This deficiency hampers their ability to reduce mitigate destabilizing impacts. While other government agencies, such as USAID, have developed expertise in crafting pre-crisis action items, it is crucial that these plans also incorporate proactive measures to anticipate and mitigate the impacts of extreme weather events, including flooding, hurricanes, and droughts. Prioritizing international military education for nations most vulnerable to climate-related threats could also provide long-term benefits, enabling these nations to better help themselves at early stages.

Enhancing Humanitarian Assistance and Disaster Relief Capabilities: As the conditions that form the most fundamental aspects of climate change amplify the frequency and severity of natural disasters, there is a pressing need for the Department to elevate its HADR capabilities to effectively navigate these challenges. With natural disasters becoming more numerous, the costs more substantial, and the number of lives at risk greater,[227] it is essential for the Department to prepare for an uptick in humanitarian actions. Establishing a high-level working relationship with international bodies such as the United Nations, the upper echelons of the DoD, and various regional organizations at the Combatant Commander level is crucial and could play an essential role. It is also important for these bodies to understand how the Department can assist when requested through official channels and to be aware of any restrictions that might limit the deployment of maximum resources in a HADR event. Moreover, the opening of the Arctic and the increasing migration to coastal regions pose significant new challenges that will require robust humanitarian responses in new regions, requiring the development of new capabilities, and the forging of new relationships.

227. "What's Driving the Boom in Billion-Dollar Disasters? A Lot," Pew, October 12, 2023, https://www.pewtrusts.org/en/research-and-analysis/articles/2023/10/12/whats-driving-the-boom-in-billion-dollar-disasters-a-lot; "2022 U.S. billion-dollar weather and climate disasters in historical context," NOAA, Jan. 10, 2023, https://www.climate.gov/news-features/blogs/beyond-data/2022-us-billion-dollar-weather-and-climate-disasters-historical; "NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2024)," NOAA, https://www.ncei.noaa.gov/access/billions/.

Findings and Recommendations

Finding 10

Worldwide adaptation measures to climate change are compromised by nationalistic behaviors and opportunistic adversaries in conflict-prone regions.

Recommendation 10.1

[DOS, USD(P)] Reorient U.S. diplomatic efforts to align objectives and resources with allies and partner nations to facilitate a coordinated approach to climate change adaptation. Near term (0-2 years).

Recommendation 10.2

[CCMDs, Defense Security Cooperation Agency (DSCA)] Conduct pre-crisis coordination with other USG agencies and international bodies to maximize an efficient DoD role if requested in a HADR crisis. Near term (0-2 years).

Recommendation 10.3

[CCMDs] In collaboration with DOS and USAID, include resiliency and HADR requirements as part of Theater Security Cooperation, State Partnership Program, and International Military Education & Training activities with at-risk nations. Medium term (3-5 years).

Finding 11

DoD can enhance effectiveness in adaptation and resiliency to climate change by coordinating with Allies and leveraging commercial entities.

Recommendation 11.1

[USD(R&E)] Support sustainable climate funding in dual-use critical technologies with Allies and partners. Medium term (3-5 years).

- [USD(R&E)] Explore DoD R&D participation in the NATO Innovation Fund. Near term (0-2 years).
- [Office of Strategic Capital, Defense Innovation Unit (DIU)] Establish set-aside programs for dual-use technologies focused on force readiness and climate security in collaboration with the Small Business Investment Company Critical Technology Initiative. Medium term (3-5 years).

Enhanced Climate Security Diplomatic Example Solutions

Below, we explore example solutions that demonstrate how strategic initiatives and partnerships, leveraging U.S. leadership in technology and international collaboration, can strengthen global climate resilience and security.

Strengthening International Partnerships through the State Partnership Program

The State Partnership Program offers a valuable platform for expanding joint climate preparation efforts between the United States and partner nations. Using existing partnerships, the DoD can help with knowledge exchange, collaborative planning, and capacity-building initiatives focused on climate resilience. Strengthening these partnerships would enhance the effectiveness of disaster response efforts and foster greater regional stability and cooperation in confronting the shared challenges of a changing climate.

Investing with U.S. Allies in Developing, Scaling, and Disseminating Emerging Technologies for Climate Solutions

Supporting innovation initiatives like NATO's Innovation Fund,[228] along with global research and development partnerships, is pivotal. These efforts can broadly benefit humanity, mirroring the transformative global impact of technologies like the Global Positioning System (GPS). The DoD partnering with allies to push the development, scaling, and dissemination of technology areas critical to addressing climate change impacts, such as advanced battery technology, small modular reactors (SMRs), and fusion energy, in which the U.S. is a leader, would also bring tremendous value. The DoD's role extends beyond preparing for future conflicts; it involves partnering with global allies to develop innovative technologies and craft solutions to future security challenges.

Section Summary

The DoD can enhance its response to the international security implications of significant climate change by adopting a more proactive and strategic approach. Leveraging international cooperation and innovative solutions, the DoD can strengthen U.S. climate security, bolster global resilience, and mitigate the adverse effects of climate change on vulnerable communities and critical infrastructure around the world. A commitment to a multilateral approach, coupled with localized adaptation strategies, engagement with the private sector, and strategic foresight, will fortify the resilience of DoD operations. Moreover, internal collaboration with the interagency and educating its workforce are critical steps to support the Department's principal national security mission and effectively address the challenges posed by climate change. This recommended strategic orientation would not only reinforce national security but also position the DoD as a global leader in climate resilience.

228. "NATO Innovation Fund," https://www.nif.fund/.

Conclusion

This study intends to aid the Department of Defense as it prepares for the global implications of climate change. The recommendations herein are a work in progress since preparing for and adapting to a rapidly changing climate demands a continuous effort from within the U.S. and abroad.

The list of what must be done is long but central to this strategy. At the top of this list, the Department must consolidate the disparate entities within DoD into a distinct, single entity to better merge the climate data, models, simulations, and support tools used throughout the Department. The Board recommends establishing this single climate planning cell to better utilize and integrate climate modeling and data sources. Consolidating expertise and resources across the Department will help give this joint planning cell a single focus to enhance the DoD's broader understanding of climate impacts and implications, and therefore, establish better decision-support tools for decision-makers.

Emerging sub-seasonal-to-seasonal and seasonal weather models, artificial intelligence methods, and exascale computing advances offer promising opportunities to improve regional climate modeling at relevant scales. Harnessing the power of high-performance computing will help the Department refine its predictive capabilities and better anticipate the impacts of climate change on various operational theaters at a higher level of fidelity. This enhanced modeling capability, together with new and enhanced sources of data relevant to the DoD, enables more precise planning and risk assessment, informing decision-making processes across the organization.

Collaboration across government agencies is another cornerstone of the DoD's response to the changing climate. Working in concert with interagency partners through the U.S. Global Change Research Program and other consortiums supercharges ongoing, multifaceted efforts. The U.S. federal, state, and local entities are more productive when diverse perspectives, experiences, resources, and capabilities are brought together. The DoD is very much part of this. The Department can better enhance its situational awareness and develop much-needed integrated solutions to climate-related challenges through joint initiatives and information sharing.

In addition to technological advancements, the DoD recognizes the importance of educating its workforce. The Department is unique in employing a broad swath of the U.S. Mostly, the people of the U.S. understand the implications of climate change on the individual scale. But the ability to reinforce how the rapid onset of changing global weather patterns influence aspects of the national security mission by injecting climate considerations into planning situations, including warfare scenarios, is of incalculable value. Incorporating climate-related variables into military exercises and training programs gives those service members further exposure on how to operate in a diverse and dynamic environment, thereby enhancing their safety and the probability of mission success.

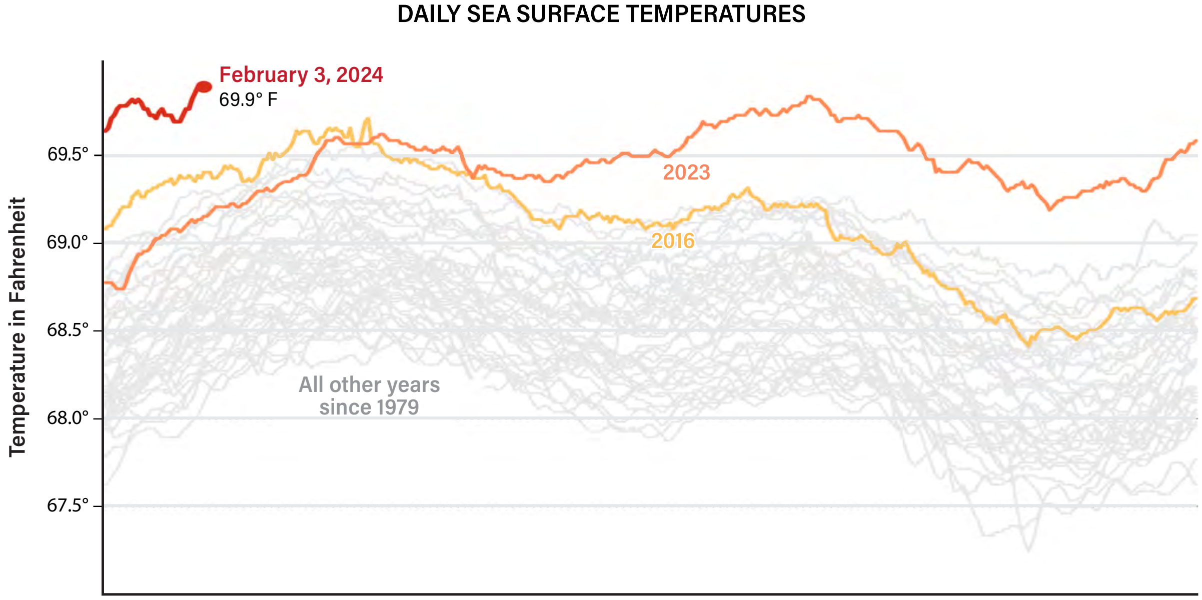

Figure 55. Surface temperatures.[229]

The human effects of a changing climate, particularly soaring temperatures and increased disease outbreaks, pose significant challenges to our service members and to global health. As temperatures rise, the incidence of heat-related illnesses and heat stress escalates. The changing climate creates favorable conditions for the spread of vector-borne diseases such as malaria, dengue fever, and Lyme disease, even in the U.S., and burdening healthcare systems everywhere. Biosurveillance becomes crucial in monitoring and mitigating these risks. The melting of permafrost introduces yet another threat vector of long-frozen viruses and bacteria. Hence, monitoring the force takes on greater importance as the force is exposed to wider temperature variances—hot and cold. Effective bio surveillance systems safeguard the health and readiness of military personnel and contribute to broader public health resilience against the escalating impacts of climate change.

During the Board's work, sizable additional climate data came to light. For instance, recent measurements of sea surface temperatures found that 2023 marked the highest worldwide sea surface recordings ever.[230] The escalating sea surface temperatures have profound implications for national and international security landscapes. As oceanic temperatures surge, the frequency and intensity of extreme weather events like hurricanes and typhoons are expected to amplify, posing significant threats to coastal infrastructure, economies, and human lives. Such disruptions can trigger mass displacements and exacerbate existing socio-economic vulnerabilities, potentially catalyzing conflicts over dwindling resources and territorial disputes.

Furthermore, the melting of polar ice caps due to rising temperatures will lead to heightened competition for access to newly accessible Arctic shipping routes. The advantages of shorter shipping lanes and access to untapped natural resources will be counterbalanced by escalating geopolitical tensions among nations. The changing geopolitical landscape underscores the need to prepare for

229. Figure 55 Source: Elena Shao, NYT; Copernicus Climate Change Service/ECMWF, https://www.nytimes.com/2024/02/07/climate/2024-hottest-january-data.html.

230. "Copernicus: 2023 is the hottest year on record, with global temperatures close to the 1.5°C limits," Copernicus, Jan. 9, 2024, https://climate.copernicus.eu/copernicus-2023-hottest-year-record.

greater presence missions and integration with Allies. Investment in Arctic-specific training, health effects, equipment, and infrastructure is increasingly apparent. Consequently, like-minded nations must prioritize comprehensive adaptation strategies, assert influence, strengthen collaborative frameworks for resource management, and engage in diplomatic efforts to mitigate long-term security risks and international tensions.

The Department of Defense's holdings of real estate, over 667,760 assets located on nearly 26 million acres worldwide, speaks to the need to protect its real investments from the impacts of a changing climate.[231] Resilience in the form of mitigation and adaptation measures can be conducted by implementing hi-tech surveillance systems, taking early measures to protect against storms, and integrating climate considerations into facility repair, upgrades, design, and maintenance.

To conclude, the Department of Defense is taking proactive steps to respond to the complex and evolving challenges of climate change. Through enhanced coordination, improved modeling across spatial and time scales of relevance, increased data gathering and usage, interagency collaboration, technological innovation, workforce education, strategic presence in key regions, and facility protection measures, the DoD will be able to anticipate, prepare, and adapt to a climate-changed future and ensure our readiness to respond to new challenges and threats as they emerge. Our national security depends on it.

231. Department of Defense, *FY2023 Base Structure Report,* (Office of the Assistant Secretary of Defense for Energy, Installations, and Environment, 2022), https://www.acq.osd.mil/eie/bsi/BEI_Library.html.

Findings and Recommendations

Findings	Recommendations
Climate Situational Awareness and Decision Support	
1. Climate modeling efforts and data sets exist. However, these are insufficient, not tailored to defense systems, not downscaled to regions or time scales of interest, and do not incorporate classified data sets.	**1.1.** [DepSecDef, CCMDs, ASD(EI&E)] Create a DoD Climate Planning Cell to generate and integrate climate data and decision support tools to guide climate-informed policy, strategy, and mission planning, including assessment of climate change impacts on adversaries. Immediate implementation (0-1 year). **1.2.** [DoD Climate Planning Cell] Working with Air Force Weather Squadron, Navy, DARPA, NGA, NASA, NOAA, consolidate and collect more global sensor network data, including creating a global undersea sensing network, for persistent fusion of atmosphere, ocean (surface and subsurface), terrestrial, and cryosphere information data. Near term (0-2 years). **1.3.** [ASD(EI&E), USD(R&E)] Continue to work with the DOE, the interagency and other experts, and the IC to leverage exascale and other computing methods for development of future global and regional scale climate models accurate at DoD-relevant operational time scales of one to ten years. Near term (0-2 years). **1.4.** [DoD Climate Planning Cell, USD(R&E)] Working with ASD(EI&E), Air Force, Navy, the Joint Staff, and others, inform NOAA, NASA, and DOE of key CCMD requirements and couple Global Climate Models (GCM) downscaled to relevant regions with advanced sub-seasonal to seasonal weather prediction tools for future DoD operations planning. Medium term (3-5 years).
2. There is a need for enhanced operational climate education and training across the Services.	**2.1.** [USD(P)] Triennially revisit and update DoD's Climate Risk Analysis. Develop guidance and policies for CCMDs and military operational planners to respond to these evolving realities. Immediate implementation (0-1 year). **2.2.** [OUSD(P&R)/DASD (FE&T), JS J7, Services] Enhance climate literacy for strategic planners and operational support personnel, integrate climate considerations, planning tools, and scenarios into operational command courses, Services' Advanced Warfighting School, and courses designed for staff headquarters, and align climate planning with Allies. Near term (0-2 years).

Findings	Recommendations
3. Improved sensing is needed to detect state-sponsored climate intervention activities.	**3.1.** [DoD Climate Planning Cell] Partner with ODNI, NOAA, and NASA to develop a program to measure stratospheric aerosols and particulates for improved atmospheric modeling and to prevent strategic surprise. Medium term (3-5 years). **3.2.** [DARPA, SCO] Develop a deployable multi-purpose stratospheric aerosol and particulate sensing suite for forward-deployed units. Medium term (3-5 years). **3.3.** [DoD Climate Planning Cell] Partner with ODNI to leverage remote sensing for monitoring large-scale climate intervention activities. Medium term (3-5 years).
Force Readiness	
4. Health and human performance will be increasingly challenged by biohazards and operations in extreme weather driven by climate change.	**4.1.** [Services] Accelerate the implementation of the DSB 2022 Summer Study recommendation: [USD(R&E), ASD(NCB) & DHA] To develop technologies for untargeted, persistent, passive, distributed, and informed biosurveillance of DoD assets with a goal of providing early warning. Engage the appropriate members of the USG, i.e., Centers for Disease Control and Prevention, National Institutes of Health, Department of State. Near term (0-2 years). **4.2.** [Army, USD(R&E)] Build on current R&D programs focused on heat acclimation and treatment for heat-related injuries and illness (e.g., Warrior Heat & Exertion-Related Events Collaborative (WHEC) and U.S. Army Research Institute of Environmental Medicine (USARIEM)). Immediate implementation (0-1 year). **4.3.** [Army, USD(R&E)] Accelerate R&D into adaptation efforts for cold weather operations and treatments for cold-related injuries and illness (e.g., DARPA ICE program). Medium-term (3-5 years).
5. A global strategy for facilities management and infrastructure resilience is needed to contend with climate change's extreme weather.	**5.1.** Facilities Management / Infrastructure Resiliency [USD(P), USD(A&S), and Joint Staff] Expand federal programs to undertake a DoD-wide integrated prioritization of, and associated funding plan for, bases and facilities most at risk of climate change and of highest mission importance. Near term (0-2 years). [SERDP-ESTCP, USD(R&E), USACE] Spearhead development of resilient, structural self-healing, and hybrid barrier materials for at-risk DoD facilities. Consider leveraging DARPA BRACE, DARPA Reefense, and USACE Engineering with Nature initiatives. Near term (0-2 years). [ASD(EI&E)] Leverage technologies to monitor and alert of failing defense infrastructure (e.g., Coherent Change Detection (CCD) Synthetic Aperture Radar (SAR)). Medium-term (3-5 years). [ASD(EI&E), USD(R&E)] Assess alternative basing constructs to address the risks posed by climate change to installations, divert sites, and forward bases. Near term (0-2 years). **5.2.** [USD(A&S)] Accelerate acquisition, certification, and deployment of independent power sources, such as nuclear microreactors, and prioritize NORTHCOM microreactor demonstrator at Eielson AFB, Alaska (2026 demo). Medium-term (3-5 years). **5.3.** [USSF S5/S8] Develop contingency national security space launch resiliency options to existing climate-threatened coastal facilities. Medium-term (3-5 years).

Findings	Recommendations
6. Global DoD operations will occur in locations increasingly challenged by extreme weather and climate change conditions.	**6.1.** Polar [JS J8, USD(A&S), USD(P), USACE] Continue to develop design factors for platforms and systems to operate in polar regions. Incorporate the design factors in future acquisitions to enable expanded polar operations. Near term (0-2 years). [USSF, NGA] Update C5ISR polar requirements (include Space Development Agency and ODNI) to include emerging commercial space capabilities. Near term (0-2 years). [USD(A&S), USD(P), Joint Staff] Further refine logistics and presence needs in the Arctic. Evaluate future maritime access requirements with NATO Arctic Command and CCMDs, including increased frequency of ICEX operations (currently every other year). Near term (0-2 years). [USD(A&S), USD(R&E)] Expand development of coatings for naval/airborne platforms for ice mitigation. Leverage DARPA ICE program as applicable. Medium term (3-5 years). **6.2.** High Temperature Environments [USD(A&S), U.S. Army Aviation, NAVAIR, AFRL/AFMC] Re-examine vertical lift (e.g., FVL) and fixed wing performance. Generate specifications for electronic and mechanical components operating at "margin of safety" temperatures. Far term (5+ years). [USD(A&S), NAVSEA] Examine submarine, ship, ground, and air power and cooling requirements. Generate specifications for components operating at "margin of safety" temperatures. Far term (5+ years). [USD(R&E), NAVSEA] Leverage new biofouling coating technologies to address drag reduction (i.e., DARPA work in past and new programs in this area). Near term (0-2 years).
7. Challenges posed by extreme weather conditions exacerbated by climate change will likely increase DoD Humanitarian Assistance and Disaster Relief (HADR) operations.	**7.1.** [USD(R&E), USD(I&S), CCMDs] Leverage next-generation C5ISR/platform capabilities for immediate in situ HADR missions. Near term (0-2 years). **7.2.** [CCMDs, JS J5] Conduct scenario planning to better define requirements for increased frequency and complexity of future HADR operations. Medium term (3-5 years). **7.3.** [Regional Combatant Commands] Integrate HADR in wargames, exercises, and related curriculums for climate-induced events. Medium term (3-5 years).
Resource Scarcity and Supply Chain Vulnerability	
8. Resource scarcity and contested access to essential resources (e.g., food, water, energy) will contribute to more frequent and complex regional instability, conflict, and mass migration, particularly in regions with low adaptive capacity.	**8.1.** [DOS, USAID, OUSD(R&E)/Minerva Program, USD(I&S), CIA] Establish a capability to combine activities and data analysis supporting climate change and social and economic stability/instability assessments. Near term (0-2 years) **8.2.** [NGA] Leverage the growth in commercial remote sensing for monitoring migration, water/food scarcity, and critical resource extraction leading to potential conflict. Near term (0-2 years). **8.3.** [DoD Climate Planning Cell, Services, USD(I&S), DIA] Integrate intelligence and CCMDs regional knowledge in areas vulnerable to food and water insecurity to inform sustainable preparation of forces and on-the-ground response in areas identified as climate-vulnerable. Medium term (3-5 years).

Findings	Recommendations
9. Supply chains, including minerals and rare earths critical to DoD operations and missions often found in areas controlled or influenced by adversaries, will be further strained by climate pressures, necessitating new approaches and increased monitoring to anticipate surprise.	**9.1.** [USD(R&E), USD(A&S)] Analyze gaps in critical, climate-induced vulnerabilities to supply chains and plan for securing access to critical minerals as a part of mission objectives. Near term (0-2 years). [DLA] Increase the stockpile of rare earth and critical minerals, with a stated preference for domestically mined and/or processed materials. Medium term (3-5 years). **9.2.** [ODNI] Working with the commercial sector, leverage open source and classified intelligence and sensing to provide current information on emerging supply chain vulnerabilities due to climate threats. Near term (0-2 years). **9.3.** [USD(A&S), USD(R&E)] Coordinate with DOE on R&D investments for the efficient and sustainable provision of rare earth and critical minerals to ensure mission objectives, including development of substitutes and re-use and re-cycling strategies. Medium term (3-5 years).
Diplomacy and Opportunities in Adversity	
10. Worldwide adaptation measures to climate change are compromised by nationalistic behaviors and opportunistic adversaries in conflict prone regions.	**10.1.** [DOS, USD(P)] Reorient U.S. diplomatic efforts to align objectives and resources with Allies and partner nations to facilitate a coordinated approach to climate change adaptation. Near term (0-2 years). **10.2.** [CCMDs, DSCA] Conduct pre-crisis coordination with other USG agencies and international bodies to maximize an efficient DoD role if requested in a HADR crises. Near term (0-2 years). **10.3.** [CCMDs] In collaboration with DOS and USAID, include resiliency and HADR requirements as part of Theater Security Cooperation, State Partnership Program, and International Military Education and Training activities with at-risk nations. Medium term (3-5 years).
11. DoD can enhance effectiveness in adaptation and resiliency to climate change by coordinating with Allies and leveraging commercial entities.	**11.1.** [USD(R&E)] Support sustainable climate funding in dual-use critical technologies with Allies and partners. Medium term (3-5 years). ▪ [USD(R&E)] Explore DoD R&D participation in the NATO Innovation Fund. Near term (0-2 years). ▪ [Office of Strategic Capital, DIU] In collaboration with the Small Business Investment Company Critical Technologies Initiative, establish set-aside programs for dual-use technologies focused on force readiness and climate security. Medium term (3-5 years).

RESEARCH
AND ENGINEERING

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10 JAN 2023

MEMORANDUM FOR CHAIR, DEFENSE SCIENCE BOARD

SUBJECT: Terms of Reference – 2023 Defense Science Board Summer Study on Climate Change and Global Security

Climate change remains an enduring global problem that has significant implications for US and global security. The 2022 National Security Strategy (NSS) states that the effects of climate change will further intensify tensions "as countries compete for resources and energy advantage — increasing humanitarian need, food insecurity and health threats, as well as the potential for instability, conflict, and mass migration."[1] The Secretary of Defense called climate change an "existential threat to our nation's security," noting that the consequences of climate change will harm our installations, constrain our ability to train and operate, and trigger crises and instability.[2]

The objective of the Defense Science Board's (DSB) Summer Study on Climate Change and Global Security ("the Summer Study") is to recommend a strategy for anticipating the global stresses and possible conflict due to climate change, as well as to provide investment priorities for new systems and technology to address the near-, mid-, and far-term needs. The DSB recommendations and report should take into consideration the following tasks:

- Investigate climate change impact on global political and military stability and highlight regions where current and future security stresses may increase the possibility of regional conflict.

- Investigate new dimensions of conflict driven by climate change, including the control of resources, interference in relief efforts, and influence of mass migration.

- Assess and recommend investments in new defense capabilities to anticipate needs driven by climate change. Areas to consider include advanced sensing systems, new communication and network coverage, new platforms, and new capabilities for relief operations.

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[1] The White House. 2022. National Security Strategy. October 2022. (Page 9). Available at https://www.whitehouse.gov/wp-content/uploads/2022/10/Biden-Harris-Administrations-National-Security-Strategy-10.2022.pdf

[2] Department of Defense, Office of the Secretary of Defense. 2021. Statement by Secretary of Defense Lloyd J. Austin III on the Department of Defense Climate Adaptation Plan. October 7 2021. Available at https://www.defense.gov/News/Releases/Release/Article/2803761/statement-by-secretary-of-defense-lloyd-j-austin-iii-on-the-department-of-defen/

- Recommend areas where Allies and partners can share the responsibility to address the global security impact of climate change.

The DSB's findings, observations, and recommendations will be thoroughly discussed and deliberated on in a properly noticed and public meeting, unless it must be closed pursuant to one or more of the Government in the Sunshine Act (5 United States Code (U.S.C.) § 552b), exemptions. The DSB will provide its findings and recommendations to the USD(R&E) as the Sponsor of the DSB. The nominal start date of the study period will be within 30 days of the signing of this Summer Study Terms of Reference (ToR). In no event will the duration of the Summer Study exceed 24 months from the start date.

In support of this ToR and the work conducted in response to it, the DSB has my full support to meet with Department leaders. The DSB staff, on behalf of the DSB, may request the Office of the Secretary of Defense and DoD Component Heads to timely furnish any requested information, assistance, or access to personnel to the DSB. All requests shall be consistent with applicable laws, applicable security classifications, DoD Instruction 5105.04 — "Department of Defense Federal Advisory Committee Management Program," and this ToR. As special government employee members of a DoD federal advisory committee, DSB members will not be given any access to DoD networks, to include DoD email systems.

Once material is provided to the DSB, it becomes a permanent part of the DSB's records. All data/information provided is subject to public inspection unless the originating Component office properly marks the data/information with the appropriate classification and Freedom of Information Act exemption categories before the data/information is released to the DSB. The DSB has physical storage capability and electronic storage and communications capability on both unclassified and classified networks to support receipt of material up to the TS/SCI level.

The DSB will operate in conformity with and pursuant to the DSB's charter, the Federal Advisory Committee Act (5 U.S.C., Appendix), the Government in the Sunshine Act, and other applicable federal statutes, regulations, and policy. Individual DSB members do not have the authority to make decisions or provide recommendations on behalf of the DSB or to report directly to any Federal representative. The members of the DSB are subject to certain Federal ethics laws, including 18 U.S.C. § 208, governing conflicts of interest, and the Standards of Ethical Conduct regulations in 5 Code of Federal Regulations, Part 2635.

Heidi Shyu

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Acronyms and Abbreviations

Acronym/Abbreviation	Definition
ACTM	AI-assisted Climate Tipping-point Modeling
AFRL	Air Force Research Laboratory
AFMC	Air Force Materiel Command
AGR	Advanced Gas Reactor
AFB	Air Force Base
AI	Artificial Intelligence
Al2O3	Alumina
AMMTO	Advanced Materials and Manufacturing Technologies Office
AMOC	Atlantic Meridional Overturning Circulation
AMOS	Arctic Mobile Observing System
ASC	Arctic Security Cutters
AUTEC	Atlantic Undersea Test and Evaluation Center
ASD(EI&E)	Assistant Secretary of Defense for Energy, Installations, and Environment
ASD(NCB)	Assistant Secretary of Defense for Nuclear, Chemical, and Biological Defense Programs
BRACE	Bio-inspired Restoration of Aged Concrete Edifices
C5ISR	Command, Control, Computers, Communications, Cyber, Intelligence, Surveillance, and Reconnaissance
CBRN	Chemical, Biological, Radiological, and Nuclear
CCI	Climate Change Impact
CCD	Coherent Change Detection
CCMD	Combatant Command
CCT	Cirrus Cloud Thinning
CERL	Construction Engineering Research Laboratory
CFE-DM	Center For Excellence in Disaster Management and Humanitarian Assistance
CIA	Central Intelligence Agency
CIBORG	Commercial Initiative to Buy Operationally Responsive GEOINT
CICE	Community Ice Code
CJCS	Chairman of the Joint Chiefs of Staff

Acronym/Abbreviation	Definition
CMI	Critical Materials Innovation Hub
CMIP	Coupled Model Intercomparison Project
CNA	Center for Naval Analyses
CONUS	Continental United States
COTS	Commercial Off The Shelf
CRIDA	Climate Risk Informed Decision Analysis
CUOPS	Current Operations
DARPA	Defense Advanced Research Projects Agency
DCAT	DoD Climate Assessment Tool
DEVCOM	Combat Capabilities Development Command
DHA	Defense Health Agency
DIA	Defense Intelligence Agency
DIU	Defense Innovation Unit
DLA	Defense Logistics Agency
DoD	Department of Defense
DOE	Department of Energy
DOS	Department of State
DRC	Democratic Republic of Congo
DSB	Defense Science Board
DSCA	Defense Security Cooperation Agency
DTRA	Defense Threat Reduction Agency
E3SM	Energy Exascale Earth System Model
EEZ	Exclusive Economic Zone
EHF	Extremely High Frequency
EIS	Earth Information System
EM	Electromagnetic
EMBER	Environmental Microbes as a BioEngineering Resource
EO	Executive Order
EO/IR	Electro-Optical and Infrared
EPA	Environmental Protection Agency
EPS	Enhanced Polar System
ERB	Earth's Radiation Budget
ESB	Expeditionary Sea Base
ESPC	Navy Earth System Prediction Capability
ESTCP	Environmental Security Technology Certification Program
FEMA	Federal Emergency Management Agency
FFRDC	Federally Funded Research and Development Center
FOA	Funding Opportunity Announcement
FUOPS	Future Operations
FVEY	Five Eyes (Australia, Canada, New Zealand, the United Kingdom, and the United States)

Acronym/Abbreviation	Definition
FVL	Future Vertical Lift
FY	Fiscal Year
FYDP	Future Years Defense Program
GCAM	Global Change Analysis Model
GCM	Global Circulation Model/Global Climate Model
GEF	Guidance for Employment of the Force
GEOINT	Geospatial Intelligence
GERD	Grand Ethiopian Renaissance Dam
GHG	Greenhouse Gas
GMAO	Global Modeling and Assimilation Office
GPS	Global Positioning System
HADR	Humanitarian Assistance and Disaster Relief
HEO	Highly Elliptical Orbits
HF	High Frequency
HOTS	High Operational Temperature Sensors
HYCOM	Hybrid Coordinate Ocean Model
H2SO4	Sulfuric Acid
IC	Intelligence Community
ICE	Ice Control for Cold Environments
ICEX	Ice Exercise
IEA	International Energy Agency
IMO	International Maritime Organization
INDOPACOM	Indo-Pacific Command
INP	Innovative Naval Prototype
IPCC	Intergovernmental Panel on Climate Change
ISIS	Islamic State of Iraq and Syria
ISR	Intelligence, Surveillance, and Reconnaissance
JPEO	Joint Program Executive Office
JS	Joint Staff
JPSS	Joint Polar Satellite System
JSCP	Joint Strategic Capabilities Plan
LEO	Low Earth Orbit
LIDAR	Light Detection and Ranging
MCB	Marine Cloud Brightening
MEF	Major Economies Forum on Energy and Climate
MF	Medium Frequency
NAS	Naval Air Station
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NAVAIR	Naval Air Systems Command

Acronym/Abbreviation	Definition
NAVGEM	Navy Global Environmental Model
NAVSEA	Naval Sea Systems Command
NCEI	National Centers for Environmental Information
NDS	National Defense Strategy
NGA	National Geospatial-Intelligence Agency
NGO	Non-Governmental Organizations
NHCI	NOPP Hurricane Coastal Impacts
NMS	National Military Strategy
NOAA	National Oceanic and Atmospheric Administration
NOMARS	No Manning Required Ship
NOPP	National Oceanographic Partnership Program
NORAD	North American Aerospace Defense Command
NORTHCOM	Northern Command
NRL	Naval Research Laboratory
NRO	National Reconnaissance Office
NS	Naval Station
NSR	Northern Sea Route
NWP	Northwest Passage
ODNI	Office of the Director of National Intelligence
ONR	Office of Naval Research
OPLAN	Operation Plan
OUSD(P&R)/DASD (FE&T)	Office of the Undersecretary of Defense for Personnel and Readiness, Deputy Assistant Secretary of Defense for Force Readiness and Training
OSD	Office of the Secretary of Defense
OSTP	Office of Science and Technology Policy
OTHR	Over-the Horizon Radar
PACE	Plankton, Aerosol, Cloud, ocean Ecosystem
PBP	Partners in the Blue Pacific
PCR	Polymerase Chain Reaction
PINNS	Physics-Informed Neural Networks
PNNL	Pacific Northwest National Labs
PNT	Position, Navigation, and Timing
PPBE	Planning, Programming, Budgeting, and Execution Process
PRC	People's Republic of China
PREPARES	Providing Research and End User Products to Accelerate Readiness & Environmental Security
PSC	Polar Security Cutter
REE	Rare Earth Elements
R&D	Research and Development
RF	Radio Frequency

Acronym/Abbreviation	Definition
RPOD	Recycling at the Point of Disposal
SABRE	Stratospheric Aerosol processes, Budget and Radiative Effects
SAI	Stratospheric Aerosol Injection
SAR	Synthetic Aperture Radar
SCIF	Sensitive Compartmented Information Facility
SCO	Strategic Capabilities Office
SERDP	Strategic Environmental Research and Development Program
SFB	Space Force Base
SFF	Sea Fog Frequency
SiC	Silicon Carbide
SiO2	Silica
SO2	Sulfur Dioxide
SODA	Stratified Ocean Dynamics in the Arctic
SRM	Solar Radiation Modification
STANAG	Standardization Agreement
SVP	Sound Velocity Profile
S2S	Sub-Seasonal to Seasonal
TO2	Titanium Dioxide
TRISO	Tristructural Isotropic
UNFCCC	United Nations Framework Convention on Climate Change
USACE	United States Army Corps of Engineers
USAFRICOM	United States Africa Command
USAID	United States Agency for International Development
USARIEM	U.S. Army Research Institute of Environmental Medicine
USD(A&S)	Under Secretary of Defense for Acquisition and Sustainment
USD(I&S)	Under Secretary of Defense for Intelligence and Security
USD(P)	Under Secretary of Defense for Policy
USD(R&E)	Under Secretary of Defense for Research and Engineering
USCG	United States Coast Guard
USG	United States Government
USGS	United States Geological Survey
USINDOPACOM	United States Indo-Pacific Command
USSF	United States Space Force
UUV	Unmanned Underwater Vessels
VEO	Violent Extremist Organization
WHEC	Warrior Heat and Exertion-Related Events Collaborative


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