ARCTIC CLIMATE CHANGE AND ITS IMPACT ON HOMELAND SECUIRTY

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Abstract

This paper examines the multifaceted implications of changing environmental conditions in the Arctic for U.S. national security, highlighting both the challenges and opportunities these transformations present. As diminishing sea ice, altered wave dynamics, increased wind speeds, and emerging weather phenomena such as rogue waves and intensified lightning reshape the Arctic landscape, the need for adaptive strategies, enhanced surveillance, and robust infrastructure resilience becomes paramount. The analysis underscores the importance of leveraging technological advancements and fostering international collaboration to navigate the operational risks and strategic complexities resulting from the Arctic's evolving climate. It also explores the economic potentials unlocked by new maritime routes and the access to untapped natural resources, advocating for sustainable and cooperative approaches to regional development. Through a comprehensive examination of the dynamic Arctic environment, this paper emphasizes the United States' pivotal role in promoting security, stability, and prosperity in the region, advocating for a proactive, informed, and collaborative approach to ensure a resilient, sustainable, and beneficial future for the Arctic and its stakeholders.

Keywords: Arctic, Climate, Security

The acquisition of Alaska from Russia in 1867 positioned the United States as a key player in the Arctic region, making it one of eight Arctic nations and one of five with coastlines along the Arctic Ocean. However, it wasn't until the 1970s that the U.S. began to formalize its Arctic strategy within national policy, initiated by President Nixon's National Security Decision Memorandum 144. This document highlighted the Arctic's strategic, economic, scientific, and environmental significance, stressing the need to enhance American capabilities for operations and understanding in the region. (United States National Security Council, 1971)

In the ensuing five decades, the U.S. has engaged in extensive research to understand the Arctic, leveraging partnerships among federal and state agencies, academia, and the private sector. This collective endeavor has led to notable advancements, from construction guidelines for permafrost regions to sophisticated Arctic equipment and improved weather prediction models. Despite these achievements, our current knowledge does not fully equip us to predict the Arctic's future conditions accurately. Without improvements to forecasting capabilities, the homeland defense implications are vast.

Arctic temperatures are rising at a rate quadruple that of the global average, driving significant ecological shifts and challenging existing knowledge. This warming is uneven, with some areas, like Northern Russia, experiencing rapid temperature increases, while others, like Northern Canada and Greenland, warming more slowly. These climate changes have profound effects on construction, food sources, and the potential exploitation of the region's resources.

The paper aims to explore future climate scenarios in the Arctic and their strategic implications, particularly for U.S. security interests. It draws on the latest academic research from leading institutions in North America and Europe, and analyzes historical data to forecast potential trends. This analysis aims to elucidate the implications of climatic shifts for inhabitants and operators in the Arctic, providing guidance for preparing for future challenges.

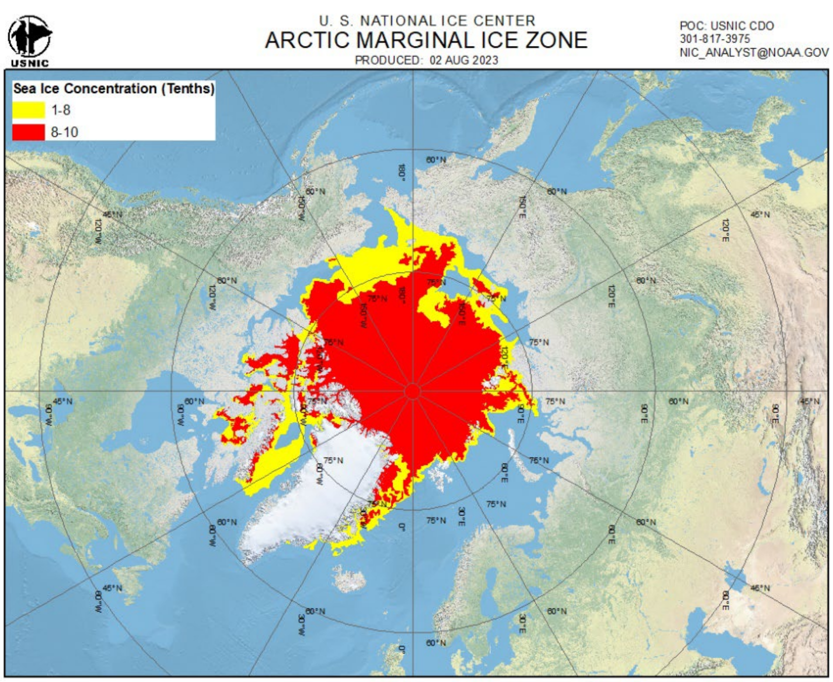
Strategic Context

Sea Ice

In the contemporary Arctic, the well-documented retreat of sea ice is characterized by the dominance of first-year ice, with multi-year ice observed in limited regions. This transformation sets the stage for a fundamental shift in the Arctic's ice dynamics, particularly within the Arctic sea ice marginal zone (MIZ). Historically, the MIZ constituted a relatively modest portion, accounting for approximately 14-20 percent of the overall Arctic ice cover (Figure 1).

Figure 1

Chart of sea ice concentration produced by U.S. National Ice Center (USNIC)



Note: Chart for 2 August 2023 (U.S. National Ice Center, 2023). Yellow indicates the current marginal ice zone and red indicates pack ice. In future decades, more yellow, and less red is predicted to appear on such charts. Figure is in the public domain.

However, recent climate models indicate a significant change on the horizon. By 2040, projections suggest a substantial expansion of the MIZ, encompassing over 90 percent of the Arctic's sea ice (Frew et al., 2023). This evolving MIZ landscape has far-reaching security implications, chiefly among them the escalation in the mobility of sea ice. With a larger portion of the ice cover now residing within the MIZ, the once stable central ice pack is diminishing, ushering in a more dynamic and rapidly shifting sea ice environment. These transformations hold critical significance for Arctic operators and planners, prompting adaptations in navigation, resource utilization, and strategic planning to address the evolving conditions.

As the sea ice changes, the landscape of wave attenuation is also undergoing a discernible transformation. Ice and waves have a complex interaction. While sea ice suppresses waves by dissipating their energy, waves simultaneously break up sea ice at the leading (outermost) edge. Whether ice or waves dominate the equation depends on ice thickness. Historically, when sea ice thickness reached a threshold of 0.5 meters or greater, wave attenuation rates were observed to be twice as high (Huang & Li, 2023). Comparisons between observed wave attenuation rates and models of future conditions suggests that when wave height and period are closely matched, older and thicker ice facilitates more rapid wave attenuation.

However, as the Arctic experiences a reduction in ice coverage and thickness across the region, a shift in attenuation rates are occurring. The diminishing and thinning ice no longer acts as an effective barrier to dampen wave energy. This development has substantial consequences, considering the increased mobility of sea ice and the expanding Arctic MIZ. This transformation will result in amplified waves within the region, impacting shorelines by accelerating erosion and block collapse along bluff faces. These changes necessitate strategic adaptations for operators and planners navigating the evolving Arctic seascape.

Surface Waves

Wave behavior in the Arctic is undergoing a transformation in response to the diminishing sea ice cover. As the expanse of pack ice retreats and the Arctic's sea ice marginal zone expands, the behavior of surface waves is gaining prominence. This shift is driven by the increased availability of open water, allowing for more extensive interactions between the wind and the water's surface. Empirical observations, satellite data, and wave models corroborate the phenomenon, demonstrating the growing fetch in the Arctic Ocean resulting from reduced ice coverage (Thomson & Rogers, 2014). In 2012, one of the first fall storms was recorded in the central Beaufort Sea, with wave heights of five meters due, in large part, to a lack of sea ice. Thomson and Rogers used this data to produce hindcast models showing the impact of storms on ice-free areas of the Arctic.

With a larger surface area of open water and the wind acting over greater distances, regional wave heights are on the rise. Projections from modeling efforts indicate that by 2100, significant wave heights will exhibit a two to three meter increase compared to current averages across much of the Arctic Ocean (Casas-Prat & Wang, 2020). This heightened surface variability increases risk for maritime surface operations, and thus has significant homeland security implications, particularly for search and rescue operations, emergency response, and general security activities. Moreover, the upsurge in wave heights, when coupled with rising sea levels, may pose additional threats to coastal communities in the region.

Another contributing factor to the increasing fetch and anticipated wave conditions in the future stems from the northward migration of polar lows (PL). Polar Lows are transient weather systems that manifest over open water or in the vicinity of the MIZ when air temperatures reach a critical cold threshold. These weather phenomena are characterized by their relatively small scale, spanning from 200-km to 1000-km in diameter, and their intense but relatively short-lived nature, persisting for periods ranging from 6 hours to a few days (Moreno-Ibáñez et al., 2021). As the sea ice retreats, climate models suggest a potential decline in the observed frequency of PLs at lower latitudes, partly attributed to the retreat of sea ice. However, as this transition unfolds, the significance of these atmospheric phenomena should not be underestimated. Polar Lows have the capacity to generate substantial wave heights, often exceeding 10 meters, along with extended wave periods. The result of these evolving climatic shifts is an increased variability in surface wave heights and unpredictability in regional weather patterns. These changes add to the challenge of maritime air and surface operations given the difficulties US weather models have accurately predicting PLs.

In the context of climate change and its impact on both Arctic shipping and maritime patrol operations, recent simulations conducted by George Mason University reveal a noteworthy shift in wave hazards within the region. As pack ice continues its retreat and opens up the Northwest Passage (NWP), their findings indicate a prospective extension of the shipping season with five months of reduced sea ice risk for maritime activities by the year 2070 (Henke et al., 2023). As the reduction in ice cover permits increased shipping activity, it also extends the seasonal period during which wave hazards are present. Historically, sea ice begins to develop in late September. If models are correct, and freeze-up shifts toward November, then extreme wave heights will coincide with freezing temperatures. The combination of these factors raises concerns about the threat of rime icing on marine vessels during this extended shipping period. This emerging hazard underscores the need for adaptive strategies and heightened vigilance by Arctic mariners and airmen to navigate the evolving Arctic seascape safely and effectively.

Wind Speed

Surface winds in the Arctic are also experiencing noteworthy changes. A study conducted by Vavrus and Alkama (2022) employed 28 models from 17 nations within the Collaborative Model Intercomparison Project Phase 5 (CMIP5) to predict the mean surface wind conditions in the Arctic through 2100. Researchers first looked at a reference period of known sea ice concentrations and mean wind speeds from 2006-2015. Past data clearly showed an anticorrelation between sea ice concentration and surface speeds. In sum, as the extent of ice covering the ocean diminished, the wind speeds increased. From here, researchers utilized various models and numerous future scenarios and to predict future changes. Results indicate an overall strengthening of wind speeds, within the range of 0.4 to 0.8 meters per second, and an approximate 13 percent overall increase in windiness across the entire Arctic region.

Seasonally, this research shows that the Arctic will experience its most significant winds during the winter months, accompanied by notable increases in wind strength during the fall. Areas where wind speeds are projected to undergo substantial increases include the Chukchi-East Siberian Seas, Franz Josef Land, and Hudson Bay. A particularly striking observation is the predicted peak in mean wind speeds, reflecting a 23 percent increase in the vicinity of Wrangel

Island, northwest of the Bering Strait. This heightened wind activity, especially during the winter season, is expected to lead to a 1.5 meters per second (m/s) increase, with considerable implications for communities in Siberia and Alaska.

Similar findings were produced by Akperov et al (2023) but using a different ensemble of climate models. Looking at future periods of 2020-2049 and 2070-2099, their results also indicated an overall increase in wind speeds across the Arctic Ocean, with regional peaks in the Bering and Chukchi Seas, and around Greenland. One curious finding was a modeled outcome showing significant decreases in wind speeds in both the Barents Sea and around Norway, despite a lack of sea ice predicted for the area.

Of importance to maritime industries are the predicted regional differences in mean wind speeds along the Northern Sea Route (NSR) and the NWP. Both of these routes are under increased scrutiny as shipping lanes and are likely to see more traffic in the coming years because of reduced sea ice. The models indicate that the NSR is poised to experience a more gradual increase in wind conditions when compared to the NWP. This distinction arises from variations in sea ice loss, where there's an accelerated loss of ice along the northern coast of Russia and more gradual losses along North America, and the intricate interplay of wind patterns across diverse Arctic regions.

These findings hold profound implications for homeland security in the Arctic region. Most importantly is the need for accurate and timely regional Arctic weather forecasts. With the Arctic exhibiting a heightened average windiness, and increasing variability in conditions, the need for precise and localized weather predictions is paramount. Secondly, the regional changes will provide some Arctic nations with calmer coastal waters, while others will have seas that are more difficult to navigate. Increasing hazardous conditions will impact coastal infrastructure, settlements, and commercial interests, notably oil, gas, and critical mineral extraction. How these conditions actually impact regional economics and geopolitics remains to be seen.

Rogue Waves

In January 2024, a rogue wave hit the U.S. Army Garrison-Kwajalein Atoll in the Marshall Islands (Lendon, 2024). Large waves are classified as "rogue" when the wave height is greater than twice the local significant wave height. For the Marshall Islands, the significant (severe) wave height is 2.91-m; the January rogue wave was 4.57-m (Bosserelle et al., 2015). The surrounding area of Roi-Namur Island, where the base is located, has an elevation of 4-m above sea level. It is no surprise, then, that the wave was devastating. But the name rogue is somewhat misleading; these wave types might be less common but occur all around the world on a daily basis, including in the Arctic.

Rogue waves had long been held as folklore until the advent of modern oceanographic technology. As recently as 1995, these extreme waves were still disregarded by science. This changed when radar data from the Goma oilfield in the North Sea provided evidence of 466 rogue waves over a 12-year span. This provided direct evidence against the assumption that rogue waves were a once in 10,000-year occurrence (European Space Agency, 2004).

In the Arctic, sources for public data on rogue waves is scant, and most recorded instances near the Arctic occur in the North Sea. Untranslated work by Russian scientists at the Marine Hydrophysical Institute of the Russian Academy of Sciences, and summarized in English by Kudenko (2023), indicate they have information, but current geopolitics preclude reaching out to determine the source of such information. Still, the English language article mentions that their scientists have models predicting 4-m waves at least 6 times a year, 8-m waves occurring two to three times a year, and 10-m waves about once a year. The article goes on to say that 15-m waves in the Arctic are a once a decade event.

Where such rogue waves occur is another matter. Scientists are still studying how they develop and which areas are prone to experiencing large wave events. However, reduced sea ice, increased wave activity, and increased wind in the Arctic signal a future environment more prone to significant waves. In combination with relatively low elevation along coastal areas of the Arctic, rogues waves may well cause geophysical, safety, and livelihood security considerations for both terrestrial communities and future Arctic mariners.

Arctic Cyclones

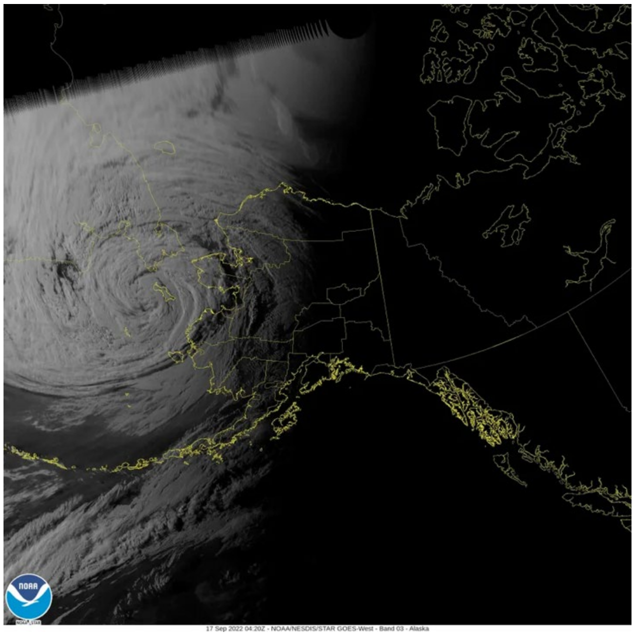
The distinction between hurricanes, cyclones, and typhoons lies in their geographical naming conventions, yet all represent the same meteorological phenomenon: a rotating, organized system of clouds and thunderstorms (NOAA, 2024). Typically, these storms form in mid-latitudes when the temperature of ocean water in the upper 50 meters reaches at least 27°C (80°F), creating atmospheric instability from the heat exchange between the ocean and air, which fuels the convective process and storm intensification. Arctic cyclones, distinct with their "cold cores," depend on factors such as sea ice concentration (SIC), turbulent heat flux, static stability, and vertical wind shear. Unlike equatorial hurricanes, Arctic storm intensification is driven by the convergence of two different air masses with varying temperatures.

The presence of sea ice significantly influences Arctic cyclones. Abundant sea ice limits the turbulent heat flux between the ocean and the atmosphere, while minimal ice allows for unrestrained energy transfer. Recent research by Crawford et al (2022), has shown that Arctic cyclones intensify in areas with reduced sea ice, particularly during fall and winter, and are associated with increased precipitation. The distribution of sea ice is also affected, with an increase on the western edge of a cyclone and a decrease on the eastern edge due to wind rotation around the storm's core (Clancy et al., 2022).

Coastal Arctic communities are increasingly vulnerable to the impacts of these storms as sea ice cover diminishes. In September 2022, Typhoon Merbok (Figure 2) struck Alaska's western coast, bringing storm surges and high winds, which, in the absence of sea ice that traditionally tempered the effects of such storms, resulted in significant flooding and water damage (Chappell, 2022). These storms can also bring warm winds and heavy rainfall, creating geophysical security concerns by accelerating permafrost thaw and damaging critical infrastructure.

Figure 2

Typhoon Merbok in 2019



Note: The remnants of Typhoon Merbok hover over Western Alaska bringing significant rain and storm surge to the region. Image credit: NOAA/NESDES/STAR (Thoman, 2022). Figure is in the public domain.

With ongoing Arctic warming and diminishing sea ice, more intense winter storms may become the norm. This underscores the importance of improving regional weather models and response strategies. In contrast to the southern United States, where communities and government agencies collaborate on storm preparedness, Alaska's response mechanisms are less developed. As the Arctic environment evolves, weaker static stability and stronger wind shear are expected to promote the development of more cyclones, highlighting the need for enhanced preparedness and response capabilities in the region.

Polar Lows

Polar lows are distinctive meteorological phenomena occurring near the poles, resembling tropical cyclones in their formation from the interaction between cold, dry air and the warmer ocean surface. Characterized as mesoscale, or intermediate sized, events, they typically span around 300-km in diameter and last between 12 to 32 hours (Stoll, 2022). Known for their swift development and severe local weather conditions, polar lows can generate strong winds, heavy snowfall, and turbulent seas, with wave heights sometimes exceeding six meters, including occurrences of rogue waves (Moreno-Ibáñez et al., 2021). The North Atlantic is notably the most frequent host of these systems (Stoll, 2022).

With the ongoing shifts in global climate, the formation sites and frequency of polar lows are evolving. In the Arctic, they are increasingly forming near the marginal ice zones and over areas with higher sea surface temperatures, prompted by the retreating ice. Climate models predict a northward shift in the formation regions of future polar lows (Moreno-Ibáñez et al., 2021), accompanied by an anticipated 15 percent decrease in their average occurrence (Romero & Emanuel, 2017). In specific regions like the Nordic Seas, the frequency of polar lows is expected to decline during the winter months, albeit with a slight increase in March. The scientific community remains divided over how these changes will affect the intensity of such systems.

The potential decrease in polar lows might reduce weather related risks for Arctic maritime activities, but it also signals broader climatic implications. Such a reduction in mesoscale storms is linked to diminished large-scale ocean circulation, notably affecting the Atlantic meridional overturning circulation (AMOC) (Condron & Renfrew, 2013). The AMOC's crucial role in redistributing heat across latitudes means that weakening the Atlantic Ocean’s ability to mediate temperature conditions could profoundly impact marine ecosystems, weather patterns, and global food security. Furthermore, such alteration may significantly influence human migration, as changing conditions render certain regions less habitable.

Lightning

Recent observations have highlighted an increasing threat from thunderstorms in the Arctic, a region where such phenomena were historically rare. A notable event occurred in 2019 with the first recorded thunderstorm in the Central Arctic, approximately 300 miles from the North Pole, marking a significant shift in climatic patterns. The year 2021 saw a striking 91 percent increase in lightning activity above 80° north compared to the total detections from 2012 to 2020 (Holle & Vagasky, 2021). Research by Holzworth et al (2021) identified a linear correlation between the fraction of global lightning occurring above 65° north and regional temperature rises. This trend suggests that a further global temperature increase of 0.5°C could potentially double the rate of lightning strikes in the Arctic from the levels recorded in 2020.

The year 2021 also witnessed lightning strikes on sea ice, a phenomenon of considerable environmental significance (Cappucci, 2021). Although such events are rare, the changing climate conditions, marked by warmer Arctic summers, create uncertainties about the future frequency and distribution of lightning in the region. These thunderstorms, especially those near the Central Arctic Ocean, affect a wide range of stakeholders, including mariners, SAR teams, and operators of offshore infrastructure like oil and gas platforms. Beyond the direct threat to human safety—impacting researchers, expedition participants, and indigenous populations in remote areas—lightning poses risks to critical infrastructure. It can disrupt communication systems, scientific equipment, and navigation tools, complicating both research and maritime activities. This situation emphasizes the need for effective risk management and preparedness to address the emerging challenges of lightning hazards in the Arctic.

Discussion

The diminishing sea ice in the Arctic, along with changes in wave attenuation, poses multifaceted challenges for U.S. security interests. The reduction in sea ice thickness and coverage diminishes the ice's capacity to dampen wave energy, leading to increased wave action. This development jeopardizes naval and commercial navigability and amplifies operational risks. Furthermore, the resulting erosion and geological instability threatens infrastructure, including military installations and civilian communities, necessitating strategic adaptations and enhanced resilience. The expanding MIZ also impacts strategic mobility and access, highlighting both opportunities and challenges for military and Coast Guard operations in a region of increasing geopolitical interest.

As the Arctic becomes more accessible yet unpredictable, the U.S. must adapt its security posture, infrastructure planning, and operational protocols. Enhanced surveillance and situational awareness are essential for anticipating and mitigating the risks associated with these environmental changes. The national security implications extend to maritime operations, Arctic domain awareness, and coastal community resilience, as modeling efforts predict significant increases in wave heights and wind speeds by 2100. The northward migration of polar lows and the increasing occurrence of rogue waves further complicate surface conditions, challenging both navigation and infrastructure planning. Additionally, the extension of the shipping season through the Northwest Passage introduces new hazards, such as extreme wave conditions and rime icing on vessels and infrastructure, necessitating adaptive strategies for safer surface navigation, commercial activities, and SAR operations.

The observed and projected increases in surface wind speeds, particularly around strategic locations such as Wrangel Island, Hudson Bay, and Western Alaska, significantly impact Arctic operations. These changes demand enhanced weather forecasting capabilities and a sophisticated understanding of regional weather dynamics. The variability in sea ice loss and wind patterns across the Arctic underscores the need for precise, localized weather predictions to inform decision-making, operations, and strategic planning.

Moreover, the convergence of increasing Arctic cyclones, the northward migration of PLs, intensified lightning activity, and the advent of Arctic rogue waves introduces a complex array of challenges. These environmental shifts necessitate a reevaluation of operational strategies and the development of robust risk mitigation practices. Prioritizing advancements in technology and geophysical intelligence to navigate the unpredictable Arctic environment is crucial for ensuring the safety of personnel and the security of assets. Collectively, these changes underscore the imperative for the U.S. to remain agile and informed in the face of the Arctic's evolving landscape, safeguarding national security interests while supporting Indigenous communities and maintaining regional stability.

Conclusion

The evolving environmental conditions in the Arctic, highlighted by diminishing sea ice, changing wave dynamics, increased wind speeds, and the emergence of new weather phenomena such as rogue waves and intensified lightning, present a complex tableau of challenges and opportunities for U.S. security interests. These changes undoubtedly introduce heightened operational risks and necessitate a reevaluation of strategic and infrastructural resilience. Yet, they also open avenues for enhanced collaboration, innovation, and leadership in addressing the multifaceted implications of climate change in the Arctic region.

The United States, as a key player in Arctic affairs, has the opportunity to lead efforts in developing advanced surveillance, weather prediction models, and risk mitigation strategies. Such initiatives not only safeguard national security interests but also contribute to the safety and well-being of the broader Arctic community. By embracing adaptive strategies and leveraging technological advancements, the U.S. can confidently and foresightedly navigate the uncertainties of the Arctic's changing landscape.

The shifting conditions in the Arctic also offer potential for expanded maritime routes, like the NSR and the NWP, presenting economic opportunities and the prospect of shorter global shipping paths. Coupled with the possibility of accessing untapped natural resources, these developments underscore the importance of sustainable and cooperative approaches to exploration, shared security, and development in the Arctic.

The challenges presented by the changing Arctic environment can catalyze international collaboration, and foster dialogue and partnerships among Arctic nations to address shared concerns related to security, environmental protection, and sustainable development. In this context, the U.S. can play a pivotal role in promoting research, enhancing regional governance, and advocating for responsible stewardship of the Arctic's unique and fragile ecosystem.

Embracing the dual nature of the challenges and opportunities presented by the Arctic's climate transformation will allow the United States to demonstrate leadership in promoting security, stability, and prosperity in the region. Through a proactive, informed, and collaborative approach, the U.S. can shape a future for the Arctic that is resilient, sustainable, and beneficial for all stakeholders involved. This vision ensures a peaceful, stable, and thriving Arctic for generations to come, highlighting the positive and hopeful outlook amidst the region's ongoing changes.

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