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Climate Change and Its Implications for Naval Operations and Maritime Safety

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Abstract

Climate change is altering the physical environment of the oceans through warming seas, rising sea levels, shrinking sea ice and shifts in storm and wave conditions, with direct consequences for the safety of ships and seafarers and for the planning of naval forces. This article examines the implications of climate change for naval operations and maritime safety. Drawing on climate science assessments, research on coastal impacts, polar navigation, marine ecosystems, climate-related security risks and resilience, it analyses effects on coastal naval infrastructure, severe-weather safety, Arctic operations, humanitarian demand and the energy transition, and it considers institutional adaptation. The analysis indicates that climate pressure is greatest where infrastructure is long-lived and exposed, where operations expand into harsher environments and where demand for assistance grows, while adaptation readiness remains uneven. Limitations include uncertainty in regional projections, contested links between climate and conflict and limited evidence on operational impacts. An illustrative figure summarises expected climate pressure and adaptation readiness across domains.

Keywords: climate change, naval operations, maritime safety, Arctic navigation, adaptation and resilience

INTRODUCTION

Climate change is reshaping the physical environment in which navies and merchant fleets operate. The ocean has absorbed most of the excess heat from greenhouse gas emissions, and assessments of the ocean and cryosphere document warming seas, accelerating sea-level rise, shrinking sea ice, more intense marine heatwaves and changes in storm behaviour (IPCC, 2019). These changes affect the safety of ships and seafarers, the viability of coastal naval bases, the accessibility of polar waters, the demand for humanitarian operations and the strategic calculations of states. For naval organisations, climate change is both an operational and a strategic issue. Operationally, it alters weather and sea conditions, increases the frequency of extreme events, and places new demands on ships, aircraft, bases and personnel. Strategically, it may exacerbate instability in vulnerable regions, open new maritime routes and resource areas, and increase the demand for naval forces to respond to disasters. Naval roles in protecting trade, deterring

aggression and providing assistance abroad all intersect with these developments (Till, 2013). This article examines the implications of climate change for naval operations and maritime safety. It reviews the physical changes underway, their effects on coastal infrastructure, ship safety, polar operations and ocean ecosystems, the growth of humanitarian and security demands, the implications of decarbonisation, and the institutional measures needed for adaptation. The analysis is conceptual and integrative, and the figure presented is an illustrative synthesis rather than a report of new empirical data.

Climate Change and the Marine Environment:

The scientific assessment of the physical climate system concludes that human influence has unequivocally warmed the atmosphere, ocean and land, and that many changes in the climate system are unprecedented over centuries to millennia, particularly those relating to oceans and ice sheets (IPCC, 2021). Ocean heat content has risen steadily, global mean sea level has risen at an accelerating rate, marine heatwaves have become more frequent, and the extent of Arctic sea ice has declined sharply. These changes will continue in the coming decades, with the scale depending on future emissions. The consequences for the marine environment are wide-ranging. Warmer water expands and, together with melting land ice, raises sea level. Changes in temperature and salinity alter ocean circulation and stratification, which influence weather patterns, acoustic propagation and the distribution of marine life. Absorption of carbon dioxide acidifies seawater, and decreasing oxygen levels affect marine ecosystems. Each of these changes has implications for operations, since naval and maritime activity depends on accurate understanding of the physical environment. Projections of future change carry uncertainty, particularly for ice-sheet dynamics and regional patterns of storms and circulation. Early semi-empirical approaches suggested that sea-level rise could be larger than first estimated by conventional models, illustrating the importance of treating upper-end outcomes seriously in planning (Rahmstorf, 2007). For naval and maritime planners, the central lesson is that conditions will not remain within the historical envelope on which design standards, doctrine and training were based, and that planning needs to consider a range of plausible futures.

Sea-Level Rise, Storms and Threats to Coastal Naval Infrastructure:

Naval bases, shipyards, ports and supporting infrastructure are concentrated in coastal locations that are exposed to rising seas and storm surges. Sea-level rise increases the frequency and depth of flooding, accelerates erosion and enables saltwater intrusion, and its effects are amplified by land subsidence in some deltas and cities. A broad assessment of the impacts of sea-level rise on coastal zones highlights the vulnerability of low-lying areas, the interaction of rising seas with other human and natural pressures and the long timescales over which adaptation decisions must be made (Nicholls & Cazenave, 2010). Storms add further risk. Research on tropical cyclones has reported an increase in their destructive potential in recent decades, associated with higher sea surface temperatures, which suggests that coastal facilities in cyclone-prone regions may face greater wind, rain and surge damage (Emanuel, 2005). Damage to piers, drydocks, fuel storage, power and communications can reduce readiness and delay operations, and recovery may be slow when surrounding civil infrastructure is also damaged. Ships may need to sortie to avoid storms, which has costs and operational implications. Adapting coastal installations involves structural measures such as sea walls, raised piers, flood barriers and improved drainage, alongside planning measures such as relocating critical functions, elevating equipment and diversifying basing. Long-lived infrastructure decisions made now will have to function through decades of change, so design standards should include allowances for future conditions. Because naval bases depend on local utilities, transport and communities, adaptation also requires coordination with civilian authorities and attention to regional resilience, not only to the perimeter of the base.

Extreme Weather, Sea State and Maritime Safety:

Maritime safety is closely tied to weather and sea state. Severe storms, high waves, strong winds, fog, ice and extreme heat all increase the risks to ships and crews, and they can cause groundings, collisions, cargo loss, structural damage and capsizing. Evidence from climate assessments indicates that the frequency and intensity of some extremes are changing, with more intense heavy-rain events, stronger tropical cyclones in some regions and shifts in storm tracks (IPCC, 2022). For mariners, this means that historical experience may be an increasingly imperfect guide to future conditions. The effects reach beyond individual events. Changes in wave climate and wind patterns affect fuel consumption, route planning and the timing of seasonal operations. Heat stress affects crews and equipment, particularly in engine rooms and on flight decks, and may reduce operating windows for physically demanding tasks. Warmer and more humid conditions affect electronics, sensors and weapons systems, and changes in the ocean's temperature structure affect sonar performance and therefore anti-submarine warfare. Naval planners should incorporate these effects into assessments of platform capability and readiness. Improving safety under changing conditions depends on better forecasting, risk management and training. Investment in observation systems, ocean and weather modelling and decision-support tools helps mariners to anticipate and avoid dangerous conditions, while training and simulation prepare crews to handle severe weather, heavy-weather ship handling and emergencies. Updates to ship design standards, stability criteria and operating procedures may be needed. Culture is also important, since

commanders must be able to alter or cancel operations when risk becomes unacceptable without being penalised for prudence.

Arctic Change and New Strategic Operating Environments:

The Arctic is warming faster than the global average, and the decline of sea ice is opening areas that were previously inaccessible for much of the year. Modelling studies have suggested that trans-Arctic shipping routes may become navigable for open-water vessels by the middle of the century and that ships with ice-strengthening may be able to use them far earlier and with greater regularity (Smith & Stephenson, 2013). The prospect of shorter routes between Asia, Europe and North America, together with access to offshore energy and mineral resources and to fisheries, has increased economic and strategic interest in the region. For navies, the changing Arctic raises a series of challenges. Operating in high latitudes demands ice-capable ships, cold-weather equipment, specialised training and reliable navigation, communications and search and rescue capabilities, all of which are limited in the region. Charting is incomplete, infrastructure is sparse, distances are large and the environment is unforgiving, so that accidents may have grave consequences. Greater traffic and activity will increase the likelihood of incidents, including oil spills, groundings and collisions, in an area where response capacity is thin. Strategic competition and cooperation both are likely to intensify. States are expanding their presence, modernising icebreaker and naval forces and asserting claims, which creates risks of misperception and friction, yet the region also has a history of cooperation on safety, search and rescue and environmental protection. Naval forces can contribute to stability by supporting safety and surveillance, participating in exercises with partners and respecting established legal frameworks. Preparing for Arctic operations requires long-term investment in capability, and it should proceed alongside diplomatic efforts to preserve cooperation.

Ocean Warming, Acidification and Marine Ecosystem Change:

Changes in ocean temperature and chemistry are transforming marine ecosystems, with consequences for food security, livelihoods and stability. Reviews of the evidence show shifts in species distribution, changes in the timing of biological events, declines in some fisheries and risks to coral reefs and other sensitive habitats as the ocean warms, acidifies and loses oxygen (Doney et al., 2012). As fish stocks migrate or decline, fishing fleets may move into new areas, sometimes crossing boundaries, which can heighten disputes and illegal fishing and increase demands on naval and coast guard forces. Ecosystem change also influences maritime security more directly. The loss of coastal protection from degraded reefs, mangroves and wetlands increases exposure to storms, and the decline of fisheries can drive economic hardship that contributes to illicit activity such as piracy or trafficking in vulnerable coastal regions. Naval forces engaged in maritime law enforcement and constabulary duties may find that their tasks expand, requiring greater surveillance of fishing activity, cooperation with other agencies and capacity building for partner states. Environmental stewardship is itself part of the naval role. Operations generate emissions, discharges, noise and potential for pollution, and navies are increasingly expected to limit their environmental footprint and to contribute to scientific understanding of the ocean. Navies collect large quantities of oceanographic data that can support climate science and environmental management, and collaboration between naval and scientific institutions can benefit both. Such cooperation strengthens legitimacy and builds knowledge useful for operational planning.

Humanitarian Assistance, Disaster Relief and Climate-Related Security Risks:

Climate change is expected to increase the frequency and severity of disasters such as cyclones, floods, droughts and heatwaves, and naval forces are often among the first responders because they can deploy rapidly, operate independently of damaged infrastructure and provide logistics, medical care, engineering and communications. Humanitarian assistance and disaster relief missions have grown in prominence, and many navies now consider them a core task. Increased demand may strain resources, reduce availability for other missions and require specialised ships, aircraft and training. The relationship between climate and conflict is complex. A synthesis of quantitative studies found that deviations from normal climatic conditions are associated with increased risks of various forms of conflict, from interpersonal violence to intergroup conflict, although the mechanisms are debated and other factors such as governance and economic development are important (Hsiang et al., 2013). Climate impacts may act as a threat multiplier, worsening existing vulnerabilities, displacing populations, straining resources and contributing to instability that in turn creates demands for maritime security forces. These findings should be interpreted carefully. Climate change rarely causes conflict directly, and deterministic narratives risk misdirecting policy. Nonetheless, naval planners should incorporate climate risk into assessments of regional stability, scenario planning and force posture, and should work with partners to build local resilience. Humanitarian operations also offer opportunities for cooperation among navies, including those that are otherwise rivals, and thereby help to build trust and interoperability.

Decarbonisation, Energy Transition and Naval Fleet Implications:

Climate mitigation is reshaping the maritime industry. The International Maritime Organization has adopted an initial strategy that aims to reduce total greenhouse gas emissions from international shipping by at least half by 2050 compared with 2008, and to pursue the phasing out of such emissions as soon as possible (International Maritime Organization, 2018). The strategy encourages energy efficiency, alternative fuels and new technologies, and it is driving

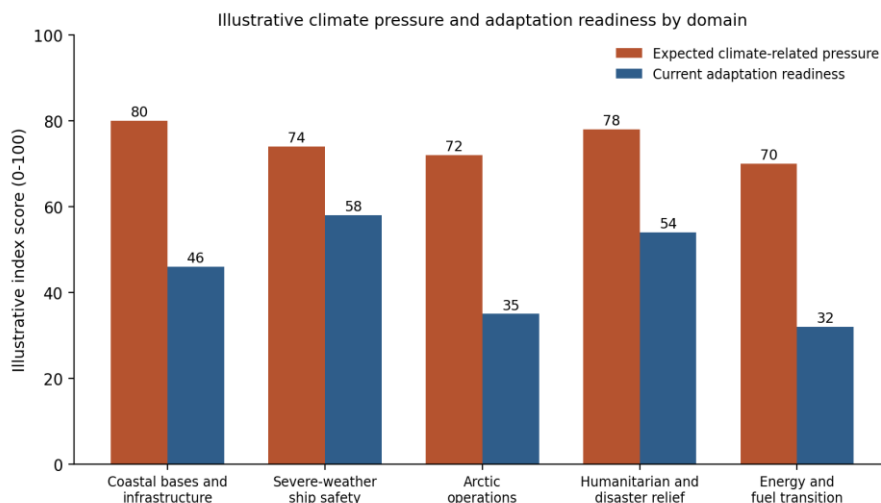
changes in ship design, fuel supply chains and port infrastructure that will affect all maritime users. Naval vessels are generally exempt from many of the commercial shipping rules because of the sovereign immunity of warships, but navies are not insulated from the transition. Many governments have set targets for reducing the emissions of defence organisations, and fuel supply networks are likely to change as commercial shipping moves to new fuels. Fuel is also a strategic vulnerability, since the logistics of supplying fuel to ships at sea are demanding and may be targeted. Greater efficiency, hybrid propulsion, alternative fuels and renewable energy ashore offer operational as well as environmental benefits, such as longer endurance and reduced logistic burden. The transition poses real difficulties. Naval requirements for power, range, speed, reliability and survivability are demanding, and technologies such as nuclear propulsion, batteries, hydrogen or synthetic fuels each have trade-offs. Decisions about future fleet design must be made under uncertainty about technology and fuel availability. A balanced approach involves incremental efficiency measures in existing ships, investment in research and demonstration, and careful assessment of the operational implications of new energy sources, so that environmental goals are pursued without compromising security.

Adaptation, Resilience and Institutional Preparedness:

Adaptation requires changes in policy, planning, infrastructure, equipment and culture. A first step is systematic assessment of climate risk, covering bases, ships, supply chains, personnel and missions, using the best available scientific information and scenarios. The findings should be integrated into strategy, procurement, doctrine, training and budgeting, instead of being treated as a separate environmental issue. Impact and adaptation assessments emphasise that adaptation is most effective when it is planned across sectors, supported by institutions and matched to local conditions (IPCC, 2022). Resilience is the guiding concept. Researchers have argued that managing risk is insufficient for complex systems facing uncertain shocks, and that planning should aim to strengthen the ability to absorb, recover from and adapt to disruption (Linkov et al., 2014). For naval forces this implies redundancy in critical functions, dispersal of assets, flexible basing, robust logistics and the capacity to improvise. It also implies investment in people, including training, leadership and organisational learning, since human adaptability is a central source of resilience.

Challenges, Limitations and Future Directions:

Several challenges complicate the response to climate change in naval and maritime contexts. Uncertainty about regional impacts and timing makes planning difficult, and the long lifespans of ships and infrastructure mean that decisions made today must cope with conditions that cannot be known with confidence. Competing priorities, tight budgets and short political cycles often push climate adaptation down the agenda, and organisational cultures focused on immediate operational demands may undervalue long-term risks. Information on climate effects may not be translated into forms useful to operational planners. There are also analytical limits. Evidence on specific impacts for naval operations is incomplete, the relationship between climate and conflict is contested, and the assessment of adaptation effectiveness is at an early stage. Overstating the security consequences of climate change can lead to the securitisation of issues better handled through development and environmental policy, while understating them leaves organisations unprepared. A balanced and evidence-based approach, with explicit treatment of uncertainty, is therefore preferable. Future directions include stronger integration of climate science into operational planning, improved ocean and weather prediction, climate-informed design standards for bases and ships, enhanced capacity for polar and disaster-response operations, and investment in low-carbon technologies suited to naval requirements. International cooperation will be important for sharing data, coordinating humanitarian response and managing shared spaces such as the Arctic. Research should focus on quantifying operational impacts, evaluating adaptation measures and understanding the pathways linking climate change to maritime security and safety.



Summary:

Climate change has significant implications for naval operations and maritime safety. Rising sea levels and stronger storms threaten coastal bases and infrastructure, extreme weather and changing sea conditions alter risks for ships and crews, the opening of Arctic waters creates new strategic and operational demands, and ecosystem change and climate-related disasters increase the need for maritime security and humanitarian operations. Decarbonisation of shipping and the wider energy transition also affect naval fuel, logistics and fleet design. Responding effectively requires systematic climate risk assessment, integration of climate information into planning and doctrine, adaptation of infrastructure and equipment, investment in forecasting, training and polar capability, and a resilience-based approach to uncertainty. Limitations include uncertain regional projections, contested causal links between climate and conflict, limited operational evidence and competing priorities. Future work should quantify operational impacts, evaluate adaptation options, develop low-carbon technologies suited to naval needs and strengthen international cooperation for shared spaces and humanitarian response.

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