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Global Warming Could Have a Chilling Effect on the Military

by Richard F. Pittenger and Robert B. Gagosian

Overview

Most debates and studies addressing potential climate change have focused on the buildup of industrial greenhouse gases in the atmosphere and a *gradual* increase in global temperatures. But this "slow ramp"[1] climate change scenario ignores recent and rapidly advancing evidence that Earth's climate repeatedly has become much colder, warmer, wetter, or drier—in time spans as short as three to 10 years.

Earth's climate system appears to have sensitive thresholds, the crossing of which shifts the system into different modes of operation and triggers rapid, non-linear, and not necessarily global changes. This new paradigm of abrupt climate change does not appear to be on the radar screens of military planners, who treat climate change as a long-term, low-level threat, with mostly sociological, not national security, implications. But intense and abrupt climate changes could escalate environmental issues into unanticipated security threats, and could compromise an unprepared military.

The global ocean circulation system, often called the Ocean Conveyor, can change rapidly and shift the distribution patterns of heat and rainfall over large areas of the globe. The North Atlantic region is particularly vulnerable to abrupt regional coolings linked to ocean circulation changes. Global warming and ocean circulation changes also threaten the Arctic Ocean's sea ice cover. Beyond the abrupt climatic impacts, fundamental changes in ocean circulation also have immediate naval implications.

Recent evidence suggests that the oceans already may be experiencing large-scale changes that could affect Earth's climate. Military planners should begin to consider potential abrupt climate change scenarios and their impacts on national defense.

A Climate of War

History is filled with examples of military leaders who have suffered at the mercy of climate conditions that they failed to contemplate adequately, or who have exploited climate conditions to great advantage. Napoleon's disastrous winter campaign in Russia immediately comes to mind as an example of the former, while the American Revolutionary War provides examples of the latter.

In his splendid, Pulitzer Prize-winning biography of John Adams, David McCullough recounts how the Colonial army mounted an expedition during the winter of 1775–76 to take cannons captured by Ethan Allen at Fort Ticonderoga on Lake Champlain and "haul the great guns back over the snow-covered Berkshire Mountains all the way to Boston, a task many had thought impossible."[2] By early March, however, General George Washington's men had positioned the guns on the Dorchester hills "looking over Boston Harbor and the British fleet," which shortly sailed away in ignominious defeat and abandoned Boston.

Bringing the cannons to Boston, McCullough wrote, was "a feat of almost unimaginable daring and difficulty and, ironically, only made possible by the severity of the winter, as the guns had been dragged over the snow on sleds."

Grim winters marked the incipient years of the Revolutionary War. The following winter, Washington crossed the Delaware River in driving sleet and snow to surprise the Hessians at the Battle of Trenton. Emanuel Leutze's famous painting depicts Washington's men pushing hunks of ice in the frozen Delaware, which rarely freezes today. The winter after that, Washington's men endured their ordeal at Valley Forge, emerging as a more confident army.

It was about this bitterly cold era that Thomas Paine wrote, both literally and metaphorically: "These are times that try men's souls. The summer soldier and the sunshine patriot will, in this crisis, shrink from the service of his country."

It is now known that the Revolutionary War took place within a climatological era known as the "Little Ice Age," a period beginning about 1350 A.D. in which average wintertime temperatures abruptly turned cooler in the North Atlantic region, and persisted that way for roughly 500 years.

All human endeavor hinges on the vicissitudes of climate, and that includes warfare. Recent evidence points to the potential for abrupt cooling in the North Atlantic region in the future. Lest military planners be caught with summer soldiers during a big chill, they

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would do well to pay attention to recent scientific advances in our understanding of the oceans and climate change.

Role of Oceans in Climate Change

Abrupt climate changes are possible, perhaps even more likely, in the future, according to a 2002 report by the US National Academy of Sciences (NAS), titled *Abrupt Climate Change: Inevitable Surprises*.[3]

The report cited wide-ranging geological evidence and computer models that demonstrate that Earth's complex and dynamic climate system has more than one mode of operation. Each mode produces different climate patterns.

The evidence also shows that Earth's climate system has sensitive thresholds. Pushed past a threshold, the system can jump quickly from one stable operating mode to a completely different one—"just as the slowly increasing pressure of a finger eventually flips a switch and turns on a light," according to the NAS report.

The same characteristics seem to be true of the global system of ocean currents, collectively known as the Ocean Conveyor. A swift reorganization of ocean circulation is a highly plausible mechanism to induce large, abrupt climate change.[4] Indeed, it is a prime suspect.

The Ocean Conveyor moves vast quantities of heat around our planet, and thus plays a fundamental role in governing Earth's climate. The oceans also play a pivotal role in the distribution and availability of life-sustaining water throughout our planet.

The oceans are, by far, the planet's largest reservoir of water. Evaporation from the ocean transfers huge amounts of water vapor to the atmosphere, where it travels aloft until it cools, condenses, and eventually precipitates in the form of rain or snow. Changes in ocean circulation or seawater properties can disrupt this hydrological cycle on a global scale, affecting the frequency and intensity of floods and long-term droughts in various regions. The El Niño phenomenon is but one example of how oceanic changes can dramatically affect where and how much precipitation falls throughout the planet.

Thus, the oceans and the atmosphere constitute intertwined components of Earth's climate system. Unfortunately, our knowledge of ocean dynamics does not match our knowledge of atmospheric processes. The oceans' essential role is too often neglected in our calculations.

An 'Achilles' Heel' in the Climate System

Here is a simplified description of some basic ocean-atmosphere dynamics that regulate Earth's climate: The equatorial sun warms the ocean surface in the tropics. That enhances evaporation, sending water vapor into the atmosphere and leaving behind salt in the tropical ocean. The Gulf Stream, a surface limb of the Ocean Conveyor, carries an enormous volume of heat-laden, salty water up the East Coast of the United States. An extension of the Gulf Stream carries these relatively warm waters northward toward Greenland, Iceland, and Europe.

This oceanic heat pump is an important mechanism for reducing equator-to-pole temperature differences. It moderates Earth's climate, particularly in the North Atlantic region. At colder northern latitudes, the ocean releases this heat to the atmosphere—especially in winter when the atmosphere is colder than the ocean and ocean-atmosphere temperature gradients increase. The Conveyor warms North Atlantic regions by as much as 5° Celsius and significantly tempers average winter temperatures.

But records of past climates—from a variety of sources such as deep-sea sediments and glacial ice cores—show that the Ocean Conveyor has *slowed* and *shut down* several times in the past. This shutdown curtailed heat delivery to the North Atlantic and caused substantial cooling throughout the region. As one prominent earth scientist put it, the Ocean Conveyor may be "the Achilles' heel of our climate system."[5]

Turning Off the Ocean Conveyor

What can shut down the Conveyor? Solving this puzzle requires an understanding of what launches and drives the Conveyor in the first place. The answer, to a large degree, is salt.

The ocean is far from a homogeneous mass of salty water. Its composition varies greatly. Vast ocean currents, both on the surface and at depth, circulate various types of water masses on a global scale.

For a variety of reasons, North Atlantic waters are relatively salty compared with other parts of the world ocean. Salty water is denser than fresh water. Cold water is denser than warm water. When the relatively warm, salty waters of the North Atlantic release heat to the atmosphere, they become colder and denser, and begin to sink. (Fig. 1a and Fig. 1b)

In the seas that ring the northern fringe of the Atlantic—the Labrador, Irminger, and Greenland Seas—the ocean releases large amounts of heat to the atmosphere and then a great volume of cold, salty water sinks to the abyss. This water flows slowly southward, far beneath the Gulf Stream, into the South Atlantic and eventually throughout the world's oceans.

Thus, the North Atlantic is a primary source of the deep limb of the Ocean Conveyor. The plunge of this great mass of cold, salty water helps drive the global ocean's conveyor-like circulation system. It also helps draw warm, salty tropical surface waters northward to replace the sinking waters. This process is called "thermohaline circulation," from the Greek words "thermos" (heat) and "halos" (salt).

If cold, salty North Atlantic waters did not sink, a primary force driving global ocean circulation could slacken and cease. Existing currents could weaken or be redirected. The resulting reorganization of the ocean's circulation would reconfigure Earth's climate patterns.

Computer models simulating ocean-atmosphere climate dynamics indicate that the North Atlantic region would cool several degrees if Conveyor circulation were totally disrupted.[6] In addition, these North Atlantic cooling events have been correlated with more distant regional climate shifts, including disruptive changes in the

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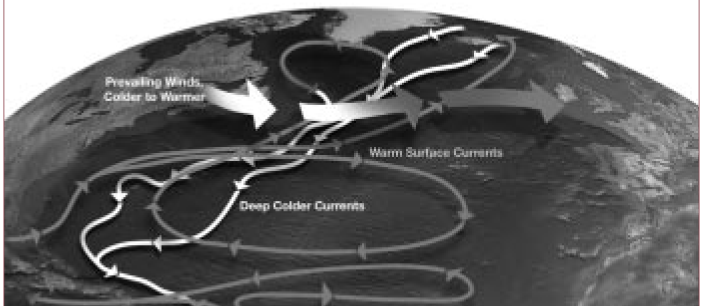
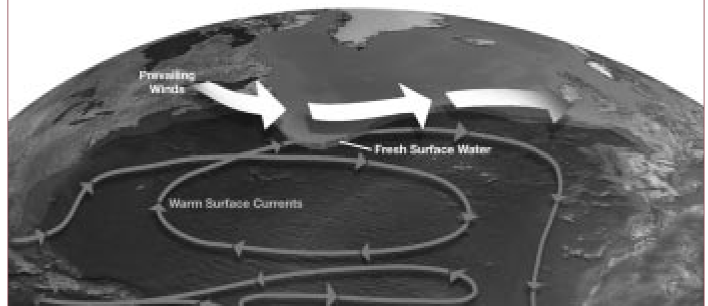
Figure 1a. The North Atlantic Ocean-Atmosphere System Today



The Ocean Conveyor is driven by the sinking of cold, salty (and therefore denser) waters in the North Atlantic Ocean (white lines). Warm surface currents (dark lines) give up heat to the atmosphere above the North Atlantic, and prevailing winds (large arrows) carry the heat eastward to warm Europe.

Source: E. Paul Oberlander/WHO1 Graphics Services.

Figure 1b. Shutting Down the Ocean Conveyor



If too much fresh water enters the North Atlantic, its waters could stop sinking. In such a scenario, warm Gulf Stream waters (dark lines) would no longer flow into the northern North Atlantic to release heat to the atmosphere. As a result, European and eastern North American winters would become more severe.

Source: E. Paul Oberlander/WHO1 Graphics Services.

South Asian monsoon, whose rains are probably the most critical factor supporting populations from Africa to India to China.[7]

It is crucial to remember several points:

- If thermohaline circulation shuts down and induces a climate transition, severe winters in the North Atlantic region may persist for decades—until conditions reached another threshold at which thermohaline circulation might resume.
- Abrupt regional cooling may occur even as the earth, on average, continues to warm. Thus, policymakers might be planning for climate scenarios of global warming that are opposite to what might actually occur in some regions.
- The timing of any Conveyor slowdown is critical: If one occurred within the next two decades, for example, the North Atlantic region could quickly and markedly cool. But if the Conveyor slowed a century from now, cooling of the North Atlantic region might partially or totally *offset* the accumulated impacts of gradual global warming. In the latter scenario, the climate of the economically developed North Atlantic region might rapidly return to one that more resembles today's—even as other parts of the world, particularly less-developed regions, experience the unmitigated brunt of global warming.[8]

Worrisome Signals in the Ocean

If the climate system's Achilles' heel is the Conveyor, the Conveyor's vulnerable spot is the North Atlantic. An influx of fresh water into the North Atlantic's surface could create a lid of fresh water, which is more buoyant and lies atop denser, saltier water. This fresh water would effectively cap and insulate the surface of the North Atlantic, curtailing the ocean's transfer of heat to the atmosphere.

An influx of fresh water would also dilute the North Atlantic's salinity. At a critical but unknown threshold, when North Atlantic waters are no longer sufficiently salty and dense, they may stop sinking. An important force driving the Conveyor could quickly diminish, with climate impacts resulting within a decade.

In an important paper published in 2002 in *Nature*, oceanographers monitoring and analyzing conditions in the North Atlantic concluded that the North Atlantic has been freshening dramatically—continuously for the past 40 years, but especially in the past decade.[9] The new data show that since the mid-1960s, the subpolar seas feeding the North Atlantic have steadily and noticeably become less salty to depths of 1,000 to 4,000 meters. The *Nature* article authors described the finding as the largest and most dramatic oceanic change ever measured in the era of modern instruments.

To date, the influx of fresher water has been mixed and distributed into the ocean. But at some point, fresh water may accumulate sufficiently in the North Atlantic to slow down or halt the Conveyor.

Signs of a possible slowdown already exist. A 2001 report in *Nature* indicates that the flow of cold, dense water from the Norwegian and Greenland Seas into the North Atlantic has diminished by at least 20 percent since 1950.[10]

Another Vulnerable Spot—the Arctic Ocean

It is generally believed that the Arctic Ocean is the canary in the coalmine of the climate system. The interactions among the Arctic region's air, sea ice, and underlying ocean circulation constitute a sensitive system that is susceptible to disruptions. These disruptions can themselves trigger further and farther ocean circulation and climate changes. Here is a simplified description of some basic Arctic Ocean dynamics:

Waters flow into and out of the largely enclosed, ice-covered Arctic Ocean through four gateways. These gateways regulate a delicate balance between relatively fresh and salty waters in the Arctic Ocean.

Pacific waters enter in the western Arctic through the Bering Sea gateway. Warmer, saltier waters—originating from the Atlantic—enter the Arctic through three other gateways: the Fram Strait, the Barents Sea, and Baffin Bay. Through these latter three gateways, cold Arctic waters also exit into the North Atlantic, where they contribute to the sinking mass of cold waters that helps propel the Conveyor. Added to this delicately balanced mix is fresh water from melting glaciers and sea ice, and from the drainage of many large rivers in Canada and Eurasia.

In the Arctic Ocean Basin, cold air temperatures freeze seawater into sea ice. This releases salt into surface waters, which become denser and sink. The process creates a thin layer of sea ice and fresh water at the surface—above a layer of denser, saltier waters, known as a halocline. (Fig. 2)

The halocline provides a barrier to mixing that would otherwise bring deeper, warmer waters in contact with the sea ice cover. The heat content of this deeper water is sufficient to melt the ice from below, adding an influx of fresh water that could flood the North Atlantic and disrupt the Conveyor.

Additional fresh water may already be entering the Arctic Ocean. There is some evidence that the volume of Arctic sea ice has decreased over the past few decades because of increased melting.[11] In addition, the average annual discharge of fresh water to the Arctic Ocean from the six largest Eurasian rivers has increased by 7 percent since 1936, according to a study published in *Science* in 2002.[12]

These signals point to global warming as a destabilizing factor. It may increase direct melting of sea ice and glaciers, and it also may be accelerating the cycle by which water evaporates and precipitates on Earth's surface.

Altering Earth's Global Water Cycle

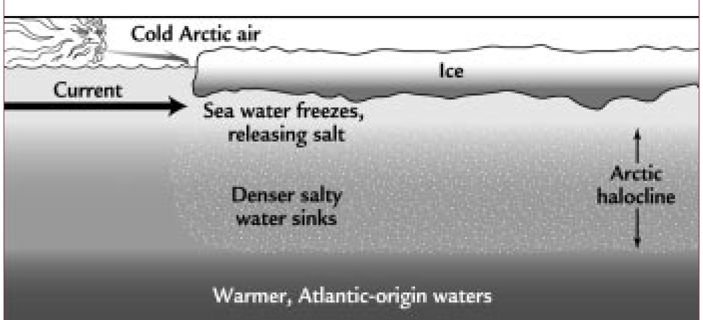
About 86% of evaporation on Earth occurs above the oceans and about 78% of precipitation falls onto the ocean surface. This continual exchange of fresh water between the oceans and atmosphere influences where and when droughts, floods, and storms occur on Earth. A warmer Earth could significantly alter this global hydrological cycle, causing tremendous, long-term consequences for society.

New data, scheduled to be published in 2003, report evidence that the global hydrological cycle may be accelerating. Over the same 40 years in which the North Atlantic has become fresher, the data show that the tropical Atlantic Ocean has become steadily *saltier*.[13] Earth's warming surface may be intensifying evaporation from tropical and subtropical oceans, concentrating salt in these oceans.

A warmer atmosphere can hold more water vapor. That, in itself, could exacerbate greenhouse warming, because water vapor itself is the most abundant, and often overlooked, greenhouse gas.

A warmer atmosphere holding more water vapor could also accelerate the atmospheric transport of fresh water from tropical regions to higher latitudes. There, it falls into the oceans as rain, diluting ocean salinity and increasing the likelihood of an Ocean Conveyor shutdown.

Figure 2. The Arctic Halocline



Arctic air temperatures freeze seawater into sea ice. Salt is rejected, creating denser waters that sink. The process creates a thin layer of sea ice and fresh water at the surface, above a layer of denser, saltier waters, called a halocline. The delicately balanced halocline provides a barrier to mixing that would otherwise bring deeper, warmer waters in contact with the sea ice cover. The heat content of this deeper water is sufficient to melt the ice from below.

Source: Jack Cook/WHOI Graphics Services.

Critical Thresholds

At what salinity threshold will the Ocean Conveyor cease? What are the ocean mixing and circulation processes that create, maintain, and threaten the Arctic halocline?

The short answer to both these questions is: We do not know.

Though we have invested in, and now rely on, a global network of meteorological stations to monitor fast-changing atmospheric conditions, we do not have a system in place for monitoring slower-developing, but critical, ocean circulation changes.

Historically, most oceanographic measurements were taken by research ships and ships of opportunity for anti-submarine warfare purposes, especially during the Cold War. Many were taken incidentally by Ocean Weather Stations (OWS), a network of ships stationed in the ocean after World War II, whose primary duty was to guide transoceanic airplane flights. Starting in the 1970s, satellite technology superseded these weather ships. The demise of the OWS network and the end of the Cold War have left oceanographers with access to *far less* data in recent years.

Initial efforts to remedy this deficit are under way, but these efforts are nascent, and time is of the essence. Satellites can measure wind stress, sea surface temperatures, ocean color, and ocean circulation globally, but they can observe only the ocean's *surface*, not the crucial processes occurring in the ocean's interior.

Also, recently launched (but not nearly fully funded) is the Argo program—an international program to seed the global ocean with an armada of some 3,000 free-floating buoys that measure *upper* ocean temperature and salinity. Measuring *deep* ocean currents is critical for observing Ocean Conveyor behavior, but it is more difficult. Efforts have only just begun to measure deep ocean water properties and currents at strategic locations with long-term, moored buoy arrays. Vast ocean voids remain unmonitored.

Ocean salinity changes that affect the hydrological cycle, ocean circulation, and climate also have not been adequately monitored. New instruments, such as salinity drifters, are being developed to take these critical measurements, but they have not been deployed in any appreciable numbers.

The Past Predicts the Future

Revealing the past behavior of Earth's climate system provides powerful insight into what it may do in the future. Geological records confirm the potential for abrupt thermohaline-induced climate transitions that would generate severe winters in the North Atlantic region.

About 12,700 years ago, as Earth emerged from the most recent ice age and began to warm, the Ocean Conveyor was disrupted. *Within a decade*, average temperatures in the North Atlantic region plummeted nearly 10° Celsius.

This cold period, known as the Younger Dryas, lasted 1,300 years. It is named after an Arctic wildflower. Scientists have found substantial evidence that cold-loving *dryas* plants thrived during this era in European and US regions that today are too warm to sustain *dryas*. Deep-sea sediment cores show that icebergs extended as far south as the coast of Portugal. The Younger Dryas ended as abruptly as it began. Within a decade, North Atlantic waters and the regional climate warmed again to pre-Younger Dryas levels.

A similar abrupt cooling occurred 8,200 years ago.[14] Average temperatures spanning from Canada and the eastern US to Europe and Alaska dropped about 5° C. Drier and windier conditions prevailed, and regions spanning from North America to Asia and Africa experienced widespread droughts. This cold, dry period lasted only about a century—a blip in geological time, but a catastrophe if such a cooling occurred today. The cause of this so-called 8,200-year event appears to have been a rapid influx of fresh water into the North Atlantic, caused by a breach in a large inland lake.

'Little Ice Ages' and 'Mega-Droughts'

Scientists are investigating whether changes in ocean circulation may have played a role in causing or amplifying the Medieval Warm Period, when, starting about 1,000 years ago, average winter temperatures in the North Atlantic region abruptly warmed by a degree or two. That was warm enough to allow the Norse to establish settlements in Greenland.

Then, starting in about 1350 A.D., the climate of the North Atlantic region turned abruptly colder, until about 1850. This period, known as the "Little Ice Age," was characterized by abruptly shifting climate regimes and more severe winters. It had profound agricultural, economic, and political impacts in Europe and North America and changed the course of history.

During this era, the Norse abruptly abandoned their settlements in Greenland. The era is captured in Leutze's painting of Washington crossing the frozen Delaware and in the frozen European landscapes of Pieter Bruegel's 16th-century paintings. But the era is also marked by persistent crop failures, famine, disease, and mass migrations. "The Little Ice Age," wrote Brian Fagan, Professor of Archaeology at the University of California at Santa Barbara, "is a chronicle of human vulnerability in the face of sudden climate change."[15]

A bad winter or two brings inconvenience that societies can adapt to with small, temporary adjustments. But a persistent string of severe winters, lasting a decade or more, can cause glaciers to advance, rivers and harbors to freeze, and sea ice to grow and spread, as well as agricultural disruptions.

Societies are similarly vulnerable to abrupt climate changes that can turn a year or two of diminished rainfall into prolonged, severe, widespread droughts. A growing body of evidence from joint archaeological and paleoclimatological studies is demonstrating that abrupt climate shifts may be linked to "mega-droughts" that precipitated collapses of civilizations—including the Akkadian empire in Mesopotamia 4,200 years ago, the Mayan empire in Central America 1,100 years ago,[16] and the Anasazi in the American Southwest in the late 13th century.[17]

Planning for Potential Climate Change

How have governmental agencies responded to the potential for climate change? In recent years, the Department of Defense, the US Army Corps of Engineers, the Environmental Protection Agency, and other agencies have acknowledged that climate change does pose potential problems.[18] But these agencies have largely focused on gradual warming forced by atmospheric change.

The EPA's Web site on climate change, for example, says that "Increasing concentrations of greenhouse gases are likely to accelerate the rate of climate change," and lists several impacts, including warmer global surface temperatures, increased evaporation and precipitation, declining soil moisture, more frequent storms, and rising sea levels.[19]

"Global warming poses real risks," but "the exact nature of these risks remains uncertain," the EPA site reads. "These uncertainties will be with us for some time, perhaps decades. Ultimately, this is why we have to use our best judgment—guided by the current state of science—to determine what the most appropriate response to global warming should be."

Similarly, the prevailing US military attitude is that a wealthy superpower has ample time and resources to adapt to gradual and anticipated climate change. In the meantime, the primary US military strategies on climate change involve publicized efforts to reduce greenhouse gas emissions and fuel consumption. They foresee few, if any, climate-induced security threats.[20]

Direct and Indirect Military Impacts

Environmental changes, however, can precipitate security threats. A widely cited paper by Richard Ullman of Princeton University, "Redefining Security," defines a natural security threat as anything that can quickly degrade the quality of life of the inhabitants of a state or narrow the choices available to people and organizations within the state.[21] The two principal criteria for determining an environmental security issue, therefore, are a short onset period and a serious impact.

These are precisely what an abrupt climate change can bring—rapid changes that can have large, detrimental impacts on agriculture, water resources, energy resources, fisheries, transportation, economic activities, disaster relief, and public health (associated with climate-related, vector-borne diseases, such as malaria and cholera, for example).

Societies can adapt more easily to gradual, anticipated changes than they can to rapid, unforeseen ones. Developing countries, in particular, which lack scientific resources and economic infrastructures, are especially vulnerable to the social and economic upheavals caused by abrupt climate change. But with growing globalization of economies, adverse impacts (although likely to vary from region to region) are likely to spill across national boundaries, through human and biotic migration, economic shocks, and political aftershocks, the NAS Abrupt Climate Change report said.

It does not take a lot of imagination, for example, to envision how deleterious changes in the monsoons in South Asia (which encompasses half the world's population and several nuclear-armed nations) could quickly escalate into security threats for the United States; or how an abrupt cooling in the North Atlantic region could lead to consecutive severe winters that tax the energy resources and economies of the US and Europe—quickly degrading inhabitants' quality of life and narrowing the choices available to them.

Beyond environmental threats that could lead to war, however, abrupt climate changes could pose more specific consequences to the US military. If they occur in a 3-to-10-year timeframe, the military, without prior planning, could be in a poor position to respond in timely fashion.

Given our current state of knowledge, we cannot predict the *probability* of any abrupt climate change. But since the *possibility* is real, it seems a useful exercise to contemplate the military ramifications of potential, abrupt climate changes. Many of these stem from potential changes in the North Atlantic and Arctic Oceans. As previously noted, changes within each of these ocean basins may be interrelated and simultaneous, but let us consider each separately.

Changes in North Atlantic Ocean Circulation

In this scenario, the sinking of cold, salty North Atlantic waters is curtailed. The effects are two-fold: they could change the temperature and salinity structure of the water column, and they could lead to dramatic climate changes. Here are a few potential military impacts:

Acoustic propagation pathways. A significantly different water column structure could have dramatic effects on present-day acoustic propagation pathways in the ocean. These acoustic paths, discovered in the late 1940s, formed the basis for all of the US and allied Anti-Submarine Warfare (ASW) Sensor Systems and aided significantly in winning the ASW battle of the Cold War.[22] A rapidly changed ocean environment could invalidate existing acoustic prediction systems, which use historic climatology to calculate acoustic paths, propagation loss, bottom loss, and ambient noise.

An Ocean Conveyor shutdown, for example, could lead to windier conditions in the North Atlantic, which would increase ambient noise and force major adjustment in existing prediction systems. The existing deep sound channel could disappear, decreasing the performance of fixed acoustic surveillance systems. North Atlantic acoustic conditions may change to more closely resemble present-day pathways in the Norwegian Sea, which, in general, are characterized by half channel propagation, rather than by a deep sound channel and surface duct conditions.

Different acoustic propagation pathways would demand adjustments on all tactical platform (air, sub, surface) sensors. The changed acoustic propagation regimes would be exploitable but would require reengineering, redesign, or even relocation of systems.

Ocean environmental now-casts and forecasts. The Navy relies on good environmental data and prediction for strategic planning and everyday operations. They are a critical element of effective operations.[23] Currently, the Navy creates ocean environmental now-casts and forecasts of sea and wave heights and directions, marine and aviation weather, ocean current fronts and eddies, and long- and short-range acoustic propagation, for example. All of these products use existing models and historic climatology as their backgrounds. All would be impacted (some severely), should the climatology be invalidated by abrupt climate change.

A stormier Atlantic Ocean. A colder, stormier North Atlantic would change the Navy's ability to operate in the region. It would increase the hazard (storm damage) of operating in this strategically vital region. It would reduce the Navy's access to the shortest (great circle) routes between US East Coast ports and Europe.

Frozen harbors. If North Atlantic conditions lead to consistently cooler winters on the US East Coast, it could result in freezing harbors, particularly at Norfolk, VA, a major American strategic naval base.

Norfolk is the largest operating base of aircraft carriers and their contingents of subs, destroyers, and auxiliary support ships. The Norfolk area complex is also a major supply center, shipyard, and naval air station, where training for carrier planes takes place. Alternative ports in Charleston and Florida exist, but these have questionable capacity to handle all Norfolk ships, particularly the aircraft carriers.

The severe winter of 1976-77 provides a picture of what could be the norm if the North Atlantic region abruptly cools.[24] The waters around Norfolk, including the Chesapeake Bay and Elizabeth and Yorktown Rivers froze solid. When this ice moved, it displaced or ripped out navigation aids. Navigation on the Chesapeake and Yorktown Rivers became treacherous and was shut down or curtailed on these important waterways for significant periods of time. Ships were trapped in and out of port. Considerable expense was required to use tugs to clear harbors.

An abrupt climate change, producing several decades of severe winters, could have considerable impact on Navy ports, including the US Submarine Base in Groton, CT, as well as on all the important commercial ports on the Northeast Coast (Boston, Philadelphia, New York, Baltimore).

Cold-weather operations. During the recent, post-Cold War era, military planners have been heavily influenced by the wars in Iraq and Afghanistan and have focused on fighting in dry, dusty, warm and hot conditions. Even the series of conflicts in the former Yugoslavia found the US Navy operating in the reasonably temperate Mediterranean Sea. As a consequence, emphasis on cold-weather operations has waned across all the services.

A colder region spanning eastern North America, Europe, and Russia would require all branches of the military to review that trend and equip and train forces to operate in cold-weather environments.

Naval Operations Beyond the North Atlantic

Changes in North Atlantic Ocean circulation conceivably could lead to more distant effects in other oceans, with important ramifications for naval operations. Along the strategic Arabian coast, for example, Robert Weller, a senior scientist at Woods Hole Oceanographic Institution, has pointed out peculiar ocean-atmosphere dynamics that create narrow flows of very cool water, or jets, that extend offshore.[25] They affect the lower atmosphere—changing wind speeds, air temperature, humidity, and optical and electromagnetic propagation.

"An aircraft carrier battle group steaming into the southwest monsoon winds to recover aircraft should anticipate changes in wind speed and atmospheric turbulence as it crosses the jets" and should anticipate being "vulnerable to quiet submarines using the environmental variability of the cool jets to screen their approach," Weller said. "The carrier and screening ships should expect changes in radar, IR, and optical propagation in the air and in optical and acoustic propagation in the ocean."

Cold periods in the North Atlantic region appear to be coincident with milder monsoonal conditions in the Indian Ocean/Arabian Gulf region. An abrupt climate shift could shift monsoonal winds patterns and intensities; naval personnel would have to discover these changes and learn how to compensate for them.

An Ice-Free or Navigable Arctic Ocean. Several recent indications that the Arctic ice cap may be thinning has led to considerable discussion of the implications of a more ice-free, navigable Arctic Ocean. But this discussion has failed to consider a critical point: Large-scale Arctic Ocean changes could occur much sooner and more precipitously—if the changes are caused by changes in ocean circulation or properties—a breach in the halocline, for example—rather than by more gradual atmospheric warming.

Naval operations in an open Arctic Ocean. The melting of Arctic sea ice would turn it into a conventional open-ocean ASW environment, with none of the advantages it now affords to an adversary strategic submarine, according to the report of an April 2001 symposium ("Naval Operations in an Ice-Free Arctic") hosted by the Office of Naval Research, the Naval Ice Center, the Oceanographer of the Navy, and the Arctic Research Commission.[26] The disappearance of the ice canopy will also eliminate the haven now provided to stationary submarines by ice keels. Active sonar detection of submarines, both by ASW sonars, and by acoustic torpedoes, would become feasible. Though strategic submarines would be more vulnerable in an ice-free Arctic, the ocean would remain a geographically strategic location for such forces. The absence of sea ice would render the ocean more accessible and viable for any submarine force—ice-strengthened or not, nuclear or conventional.

Changing acoustics in an open Arctic Ocean. The melting of Arctic sea ice could expose the sea surface to winds, which could significantly change both ambient noise and acoustic propagation, according to the Ice-Free Arctic Symposium report. Wind-generated waves would increase ambient noise in the central Arctic, so that it more closely resembled a temperate ocean. Wind-generated mixing of near surface water, combined with warmer air temperatures, would diminish or eliminate the surface duct, increasing low-frequency propagation loss.

Shorter Arctic maritime routes. For centuries, the quest for safe routes across the shorter "roof of the earth" have been sought, but ice conditions have always rendered these shortcuts impassable except to the most robust icebreaking ships. A navigable Arctic would cut the distance over the Panama Canal sea route from 12,600 miles to 7,900 miles (a savings of 12 to 15 days in transit time). For ships too large for the Panama Canal, the distance (via the route around Africa) would be reduced by 6,770 miles, or 15 to 20 days. A navigable Arctic Ocean would give the United States the strategic mobility option of deploying forces, such as carrier battle groups, between theaters much more rapidly in response to national needs and tasking.

But there are also challenges associated with easier access to Arctic sea routes.[27] Easy access to both the Northwest Passage (through the Canadian Archipelago) and the Northeast Sea Route (across the top of Russia) will assuredly invoke major legal issues with both Canada and Russia under the United Nations Law of the Seas. Easier access to the Arctic also invites other nations, including their militaries, to ply these seas. That would present the US with another coast to defend and necessitate devoting or creating forces capable of safe and effective operations there.[28]

A need for more ice-capable ships. Though the Arctic Ocean's ice-covered surface may become sufficiently ice-free to encourage more ship traffic, few are suggesting that it will become completely ice-free. Thus, more, not fewer, ice-capable ships would be required.

Since the end of the Cold War, the U.S. Navy has lost a great deal of its high-latitude capabilities and is no longer well equipped for high-latitude operations. Most Arctic-capable submarines, including all the SSN 637 class, have been decommissioned since the Cold War. Only a few Los Angeles class (SSN 751) subs were built with limited ice capabilities. Post-Cold War attack submarines of the SSN 21 and Virginia classes, as well as the ballistic missile submarines, are not ice-capable.[29]

Surface ships (destroyers, cruisers, replenishment ships, amphibious ships) are not built to operate in ice. By ice-capable ship standards, they have thin hulls and are vulnerable to damage even by thin ice. Aircraft carriers probably could withstand some in-ice-operations.

Designing and building ice-capable warships is not a trivial, inexpensive, or speedy enterprise.

Current Naval Shortfalls for Arctic Operations

Projections of capability shortfalls for naval surface forces in a navigable Arctic Ocean were identified by the Ice-Free Arctic Symposium report. Key shortfalls in the current Navy program (POM 02/PR 03) included:

- Inadequate charts of the Arctic region
- Navigation training
- Electronic navigation systems
- Sensor/Weapon/Communications performance testing
- Environmental monitoring and modeling (e.g. real-time system performance prediction)
- Extreme cold weather design/modifications to existing and planned sensors and weapon systems
- Hull design and performance/stability monitoring systems
- Arctic capable damage control systems
- Ice-clearing systems for phased array radars
- Icebreakers
- War gaming in an Arctic scenario

Another indication of the low priority the Department of Defense places on Arctic issues is the status of Office of Naval Research (ONR) support for high-latitude research. ONR Arctic research funding has dropped from about $30M/year to about $3M/year.[30] Other sections of the Navy (Spawar, submarine force and naval aviation) have all but dropped out of the Arctic research/Arctic operations picture. Virtually the entire Navy Cold War Arctic infrastructure no longer exists, and the expertise of Navy-supported researchers is atrophying.

Conclusions

The debate on global change has largely failed to factor in the inherently chaotic, sensitively balanced, and threshold-laden nature of Earth's climate system and the increased likelihood of abrupt climate change. Beyond our current speculations about future global warming, it is prudent to superimpose the potential for abrupt climate change induced by ocean and atmosphere circulation changes.

The key is to reduce our uncertainty about future climate change, and to improve our ability to predict what could happen and when. A first step is to establish the oceanic equivalent of our land-based meteorological instrument network. Such a network would begin to reveal oceanic processes that influence climate and that have been beyond our ability to grasp. These instruments, monitoring critical present-day conditions, can be coupled with enhanced computer modeling, which can project how Earth's climate system may react in the future. Considerably more research is also required to learn more about the complex ocean-atmosphere processes that induced rapid climate changes in the past, and thus how our climate system may behave in the future.

Most signs, however, indicate that military planners are going in the opposite direction, assigning research and planning on climate change a low priority. That is a gamble. The challenge to military leaders is to reduce vulnerabilities by enhancing our ability to monitor, plan for, and adapt to rapid change. Ignoring or downplaying the probability of abrupt climate change could prove costly. Some current policies and planning—or lack thereof—may be ill-advised and may prove inadequate in a world of rapid and unforeseen climate change.

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