CLIMATE CHANGE AND MILITARY POWER: HUNTING FOR SUBMARINES IN THE WARMING OCEAN

Andrea Gilli, Mauro Gilli, Antonio Ricchi,
Aniello Russo, and Sandro Carniel

Climate change will have significant effects on military power, capabilities, effectiveness, and employment. Yet, scholars have paid little attention to this topic. We address this gap by investigating the effects of changing ocean conditions on anti-submarine warfare. Anti-submarine warfare capabilities exploit various physical phenomena to detect enemy submarines, principally underwater sound propagation. Underwater sound propagation depends on factors influenced by climate change, such as water temperature and salinity. Through ocean-acoustic simulations, we estimate the effect of climate change on the detection range of enemy submarines in the North Atlantic and in the Western Pacific. Our results show that, in most areas, the range of detection through underwater acoustics is contracting due to climate change.

Will climate change have direct effects on military power, capabilities, effectiveness, and force employment? Will it strengthen some countries and weaken others? These are pressing policy questions that speak to important debates in the social sciences, such as over the impact of environmental factors on the international distribution of military power.[1] Yet, despite the growing attention to climate change in the field of international relations, and the enduring debates about its implications for international security, scholars have paid little attention to how climate change directly affects military power and military operations. This neglect is particularly relevant when we consider that climatic and meteorological events have played an important role in international and military affairs, such as by contributing to the collapse of the Roman Empire, the defeat of the Spanish "Invincible Armada," or the defeat of Napoleon at Waterloo.[2] In this paper, we address these questions by investigating the effects of climate change on the oceans, and in particular on how sound travels underwater, thus contributing to the academic and public debate about the future of submarine warfare. As we show, climate change is going to affect the ability of submarines to hide from detection, with significant implications for military operations, military technology, and international security.

Submarines exploit the ocean to hide from enemy sensors such as human sight, infrared cameras, and radar systems, which makes them a very effective military platform. This is why submarines represent a particularly credible nuclear deterrent (in the form of ballistic-missile submarines), as well as a serious threat to military and civilian ships, because they can provide coastal defense, interdict strategic lines of communications, impose a naval blockade, and more generally threaten an adversary's fleet. American naval power, for instance, is a function, at least in part, of the advanced anti-submarine warfare capabilities of the U.S. Navy. American anti-submarine warfare capabilities significantly degrade the effectiveness of one of the most serious threats for any navy: enemy submarines.[3]

However, the future of submarines might be at risk. When the United States, the United Kingdom, and Australia signed the AUKUS deal in August 2021,

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[1] See, for example, Peter Engelke and John R. McNeill, *The Great Acceleration: An Environmental History of the Anthropocene Since 1945* (Cambridge, MA: Harvard University Press, 2016). For works in the social sciences about climate change, see Kenneth Y. Chay and Michael Greenstone, "Does Air Quality Matter? Evidence from the Housing Market," *Journal of Political Economy* 113, no. 2 (2005): 376–424, https://doi.org/10.1086/427462; Melissa Dell et al., "What Do We Learn from the Weather? The New Climate-Economy Literature," *Journal of Economic Literature* 52, no. 3 (2014): 740–98, https://doi.org/10.1257/jel.52.3.740.

[2] Kyle Harper, *The Fate of Rome: Climate, Disease, and the End of an Empire* (Princeton, NJ: Princeton University Press, 2017); J. L. Anderson, "Climatic Change, Sea-Power and Historical Discontinuity: the Spanish Armada and the Glorious Revolution of 1688," *The Great Circle* 5, no. 1 (1983): 13-23, https://www.jstor.org/stable/41562423; Dennis Wheeler and Gaston R. Demarée, "The Weather of the Waterloo Campaign 16 to 18 June 1815: Did It Change the Course of History?," *Weather* 60, no. 6 (December 2006): 159–164, https://doi.org/10.1256/wea.246.04.

[3] Barry R. Posen, "Command of the Commons: The Military Foundation of U.S. Hegemony," *International Security* 28, no. 1 (Summer 2003): 5-46, https://www.jstor.org/stable/4137574. For a more general discussion, see Louis P. Solomon, *Transparent Oceans: The Defeat of the Soviet Submarine Force* (Bethesda, MD: Pearl River Publishing, 2003); Owen R. Cote Jr. and Harvey Sapolsky, *Antisubmarine Warfare after the Cold War* (Cambridge, MA: MIT Security Studies Program, 1997); Owen R. Coté Jr., *The Third Battle: Innovation in the U.S. Navy's Silent Cold War Struggle with Soviet Submarines* (Newport, RI: Naval War College, 2003), 69–78; Christopher Ford and David Rosenberg, *The Admirals' Advantage: U.S. Navy Operational Intelligence in World War II and the Cold War* (Annapolis, MD: The Naval Institute Press, 2014).

a prominent scholar warned of "the coming end of the submarine."[4] Building on this analysis, an article in *The Guardian* raised the possibility that "Australia's proposed nuclear-powered submarines could be obsolete by the time they hit the water in the 2040s due to new technologies making underwater vessels 'visible.'"[5] At face value, these concerns seem warranted. Progress in sensor acuity, multi-sensor connectivity, big data, and machine learning could significantly improve anti-submarine capabilities in the future, and, in turn, deprive submarines of their capacity to exploit the ocean to hide — an outcome known as "ocean transparency."[6]

If this is true, the implications will be significant. Over the past decade, many countries have invested in submarines, and some have decided to give priority to these platforms over surface ships, a trend that, according to some, will increase in the future with submarines taking over some of the functions of aircraft carriers.[7] If ocean transparency is indeed on the horizon, these investments could be a bad bet — especially since new submarine projects take decades to complete.[8] Moreover, ocean transparency would have important implications for deterrence and warfighting. It could deprive countries of an effective means of defending their coasts and providing conventional deterrence through diesel-electric submarines. It could also make the most credible delivery system for nuclear weapons, ballistic-missile submarines, obsolete, thus jeopardizing nuclear stability.[9] Finally, ocean transparency might strengthen some countries and weaken others, for instance, by depriving the U.S. Navy of its enduring advantage in submarine warfare stemming from its very quiet submarines.[10]

We argue that existing understandings about ocean transparency rely on an unwarranted assumption — namely, that the environmental conditions of the ocean will remain constant. The ocean, however, is changing as a result of global warming, as evidenced by melting polar ice, rising sea levels, warming surface waters, changing patterns of surface and underwater currents, changes in the patterns of tropical storms and monsoons, and seawater acidification, among others.[11] These changes are expected to worsen in the future, for example with the weakening of the Atlantic Meridional Overturning Circulation, a major driver of the Gulf Stream, and the second-order effects that its possible shutdown would trigger.[12]

Drawing from scholarship in oceanography, underwater acoustics, and signal processing, we explore how climate change trends that are already evident could influence the detection of enemy submarines in the future. Submarine detection depends on the marine environment, the medium through which detectable signals travel — primarily, sound radiated by or reflected off submarines. Sound traveling underwater in turn, is a function of variables that are directly affected by climate change, such as the temperature and salinity of oceanic waters, as well as underwater currents and boundaries between water masses

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[4] Roger Bradbury, "The Sub Story No One Wants to Hear," Defense Connect, last modified September 22, 2021, https://www.defenceconnect.com.au/blog/8792-the-sub-story-no-one-wants-to-hear. See also online appendix at https://css.ethz.ch/content/dam/ethz/special-interest/gess/cis/center-for-securities-studies/pdfs/Appendix_Climate_Change_Military_Power.pdf.

[5] Tory Shepherd, "Will All Submarines, Even Nuclear Ones, Be Obsolete and 'Visible' by 2040?," *The Guardian*, October 4, 2021, https://www.theguardian.com/australia-news/2021/oct/05/will-all-submarines-even-nuclear-ones-be-obsolete-and-visible-by-2040.

[6] See James Clay Moltz, "Submarine and Autonomous Vessel Proliferation: Implications for Future Strategic Stability at Sea," Project on Advanced Systems and Concepts for Countering WMD (U.S. Naval Postgraduate School Center on Contemporary Conflict, December 2012), https://apps.dtic.mil/sti/pdfs/ADA578475.pdf; Bryan Clark, *The Emerging Era in Undersea Warfare* (Washington, DC: Center for Strategic and Budgetary Affairs, 2015), https://csbaonline.org/research/publications/undersea-warfare.

[7] Dominic Nicholls and Danielle Sheridan, "Ben Wallace: Submarines rather than ships could be the Royal Navy's future," *The Telegraph*, September 2, 2022, https://www.telegraph.co.uk/politics/2022/09/02/ben-wallace-submarines-rather-ships-could-royal-navys-future/.

[8] Lyle Goldstein, "The unintended consequences of the AUKUS deal," *Defense News*, October 29, 2021, https://www.defensenews.com/opinion/commentary/2021/10/29/the-unintended-consequences-of-the-aukus-deal/.

[9] Vincent Boulanin (ed.), *The Impact of Artificial Intelligence on Strategic Stability and Nuclear Risk, Volume I: Euro-Atlantic Perspectives* (Stockholm: SIPRI, 2019), https://www.sipri.org/publications/2019/research-reports/impact-artificial-intelligence-strategic-stability-and-nuclear-risk-volume-i-euro-atlantic; Lora Saalman (ed.), *The Impact of Artificial Intelligence on Strategic Stability and Nuclear Risk, Volume II: East Asian Perspectives* (Stockholm: SIPRI, 2019), https://www.sipri.org/publications/2019/research-reports/impact-artificial-intelligence-strategic-stability-and-nuclear-risk-volume-ii-east-asian; Petr Topychkanov (ed.), *The Impact of Artificial Intelligence on Strategic Stability and Nuclear Risk, Volume III: South Asian Perspectives* (Stockholm: SIPRI, 2020), https://www.sipri.org/publications/2020/research-reports/impact-artificial-intelligence-strategic-stability-and-nuclear-risk-volume-iii-south-asian.

[10] Zachary Keck, "How the U.S. Military Wants to Unstealth Russian and Chinese Submarines," *The National Interest* July 23, 2017; Keir A. Lieber and Daryl G. Press, "The New Era of Counterforce: Technological Change and the Future of Nuclear Deterrence," *International Security* 41, no. 4 (Spring 2017): 9–49, https://doi.org/10.1162/ISEC_a_00273; Keir A. Lieber and Daryl G. Press, *The Myth of the Nuclear Revolution: Power Politics in the Atomic Age* (Ithaca, NY: Cornell University Press, 2020), 82-84, 90-93; Sebastian Brixey-Williams, "Prospects for Game-Changers in Detection Technology," in *The Future of the Undersea Deterrent: A Global* Survey, eds. Rory Medcalf, et al., (Canberra, Australia: ANU National Security College, 2020), https://nsc.crawford.anu.edu.au/sites/default/files/publication/nsc_crawford_anu_edu_au/2020-02/the_future_of_the_undersea_deterrent.pdf.

[11] Valérie Masson-Delmotte et al. (eds.), *Intergovernmental Panel on Climate Change: Climate Change 2021 —The Physical Science Basis. Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge, UK: Cambridge University Press, June 2023), https://doi.org/10.1017/9781009157896.

[12] Sarah Kaplan, "A Critical Ocean System May Be Heading for Collapse Due to Climate Change, Study Finds," *Washington Post*, August 5, 2021.

produced by underwater environmental conditions.[13] By affecting the oceanic environment, climate change will also affect the probability of detecting enemy submarines and the range at which it can be done. Different ocean conditions in some regions might change the underwater sound landscape (soundscape) which could result in higher or lower ambient oceanic noise. At the same time, climate change could lead either to an increase or decrease in intensity of the acoustic signals radiated or reflected by submarines. As a result, distinguishing the signal of a submarine from the ambient noise might become harder or easier.

For our analysis, we focus on transmission loss: the decrease of intensity experienced by acoustic signals when travelling underwater between two points. In order to investigate whether climate change could impact anti-submarine warfare, we rely on computational ocean acoustics. We carried out a set of simulations aimed at understanding whether and how the transmission loss that sound experiences when travelling underwater would change due to changes in water temperature and salinity. For our simulations, we consider unfriendly submarines operating in the North Atlantic and in the Western Pacific for two periods, 1970–1999 and 2070–2099, the latter being a hypothetical future period. For the North Atlantic, we consider three areas: high latitudes (Greenland Sea), mid-latitudes (beyond the Bay of Biscay), and subtropical (near Tenerife).[14] For the Western Pacific, we consider three areas: mid-latitudes (Sea of Japan), subtropical (Philippine Sea), and tropical (South China Sea).[15] Our results show that, everything else equal, the acoustic detection of submarines could become significantly more difficult in the mid-latitudes of the North Atlantic and moderately more difficult in the high latitudes of the North Atlantic as the effects of climate change accelerate. In the subtropical Atlantic, conversely, we observe modest changes. Along the same lines, we observe a moderate increase in acoustic transmission loss in the subtropics and mid-latitudes of the Western Pacific, but no significant increase in the tropical Western Pacific.

Our results do not indicate that transmission loss will increase under every condition, or that the detection of submarines will necessarily become more difficult. Other factors could also change, including the adoption of non-acoustic detection systems. Our analysis suggests that trends in underwater sound propagation might make acoustic detection more difficult in certain regions, and that an extensive analysis is needed to assess the possible impacts of climate change on anti-submarine warfare. Further research should more precisely investigate the effects of climate change on anti-submarine warfare in specific scenarios.

Our paper aims at bridging the gap between "traditional" and "non-traditional" security studies by showing that climate change can affect the military balance.

Our paper makes several contributions. First, it stresses the importance of integrating climate change into security studies, a message that "non-traditional" security scholars have emphasized for the past 15 years.[16] We contribute to this debate by focusing on a realm that, to our knowledge, climate security scholars have so far not explored: the implications of climate change for military operations. In recent years, scholars and policymakers interested in the offense-defense balance, the military balance, and America's military superiority have paid increasing attention to technological change and, in particular, to emerging and disruptive technologies.[17] Technological change is, by definition, the capacity to exploit nature to one's advantage.[18] If nature changes, however, so does the degree to which or the way in which one can

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[13] Albert W. Cox, *Sonar and Underwater Sounds* (Lexington, MA: Lexington Books, 1974), 1.

[14] The geocoordinates of the three areas are, respectively: 75°N parallel, 0° meridian, 47°N 15°W, and 28°N, 20°W. Tropical latitudes are the areas between the equator and the Tropic of Cancer and between the equator and the Tropic of Capricorn (latitude 23° 26' N and S, respectively). Mid-latitudes are the areas between the Tropic of Cancer and the Arctic Circle, and between the Tropic of Capricorn and the Antarctic Circle. High latitudes are areas in the Arctic and Antarctic Circles (latitude 66° 33' N and S, respectively).

[15] The geocoordinates of the three areas are, respectively: ~41°N 134°E, ~23°N 131°E, and ~12°N 117°E.

[16] On the relevance of integrating climate change into security studies, see for example, Joshua W. Busby, "Who Cares about the Weather?: Climate Change and U.S. National Security," *Security Studies* 17, no. 3 (September 2008), 468-504, https://doi.org/10.1080/09636410802319529; Katherine J. Mach et al., "Climate as a Risk Factor for Armed Conflict," *Nature* 571 (July 2019), 193–197, https://doi.org/10.1038/s41586-019-1300-6.

[17] Michael C. Horowitz, *The Diffusion of Military Power: Causes and Consequences for International Politics* (Princeton, NJ: Princeton University Press, 2010); President of the United States of America, *National Security Strategy of the United States of America* (Washington, DC: Government Press of the United States of America, December 2017).

[18] Amartya Sen, *Development as Freedom* (New York: Anchor Books, 2000); Daniel R. Headrick, *Power over People: Technology, Environments, and Western Imperialism, 1400 to the Present* (Princeton, NJ: Princeton University Press, 2012); Walter Benjamin, *Reflections: Essays, Aphorisms, Autobiographical Writings* (New York, NY: Schocken Books, 1986), 93.

exploit it. Despite the magnitude of the immediate and future effects and implications of climate change, "traditional" security studies scholars and, to a lesser degree, national security practitioners have paid only limited attention to it.[19] Prominent academic works on the rise and fall of great powers, American primacy, military operations, and military effectiveness have largely ignored climate change.[20] Along the same lines, the Obama administration's 2014 *Quadrennial Defense Review* devotes only a couple of paragraphs to the topic, and the Trump administration's 2018 *National Security Strategy* shows no mention of climate change at all — a trend broken by the Biden administration's 2022 National Security Strategy.[21] Our paper aims at bridging the gap between "traditional" and "non-traditional" security studies by showing that climate change can affect the military balance. Thus, we urge the academic and the national security communities to pay more attention to the environment, both in terms of analyses as well as policies.[22]

Second, our paper proposes a new way to study the relationship between climate change and international security. In doing so, it reveals the opportunities for security studies if it looks outside of the social sciences and toward the "hard" sciences — in our case, climate science, oceanography, underwater acoustics, and signal processing. Drawing from these disciplines, we identify a new way in which climate change affects the military balance, and we present an approach that, to the best of our knowledge, has not yet been used to study climate security. Moreover, our analysis also enhances the understanding of climate security, given that existing works have focused mostly on "indirect pathways from climate variability and change to conflict."[23] We have identified a direct causal mechanism through which climate change will affect international security: By modifying patterns of underwater sound propagation, climate change might make the detection of enemy submarines more challenging.[24] Along the same lines, by relying on oceanic simulations, we address a key methodological challenge for political scientists: investigating future threats empirically. [25]

Third, our analysis points to a promising new strand of research in security studies that assesses the implications of climate change on military operations. In the age of advanced sensors, hiding from enemy detection and detecting incoming threats are critical for survivability and effectiveness. Concealment and detection, however, depend on the environmental conditions, whether under water, on land, or in the air. In land warfare, for instance, foliage provides ground troops with an effective and accessible means for concealment, outside of an urban environment.[26] By reducing vegetation in some areas, however, desertification threatens to eliminate or reduce such an opportunity for concealment.[27] Similarly, air defense and missile defense depends on electromagnetic propagation in the atmosphere.[28] Electromagnetic propagation, however, can experi-

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[19] Among national security professionals, some have recognized the threat of climate change. See, for example, Michael D. Bowes, *Impact of Climate Change on Naval Operations in the Arctic* (Arlington, VA: Center for Naval Analysis, 2009), https://www.cna.org/reports/2009/impact-of-climate-change-on-naval-operations; National Research Council, *National Security Implications of Climate Change for U.S. Naval Forces*, (Washington, DC: The National Academies Press), 2011, https://doi.org/10.17226/12914; Kenneth A. Stewart, "NPS Researchers Studying Effects of Climate Change on Arctic Ocean Acoustics," Naval Postgraduate School, last modified October 26, 2016, https://nps.edu/-/nps-sees-increased-foreign-enrollment-in-undersea-warfare-program.

[20] To the best of our knowledge, no work in political science, international relations, or security studies has investigated this topic. See, for example, Kenneth N. Waltz, *Theory of International Politics* (New York: McGraw-Hill, 1979); Robert Gilpin, *War and Change in World Politics* (Cambridge, UK: Cambridge University Press, 1981); Paul Kennedy, *The Rise and Fall of the Great Powers: Economic Change and Military Conflict from 1500 to 2000* (New York: Vintage, 1987); Stephen G. Brooks and William C. Wohlforth, "The Rise and Fall of the Great Powers in the Twenty-first Century: China's Rise and the Fate of America's Global Position," *International Security* 40, no. 3 (2016): 7-53, https://doi.org/10.1162/ISEC_a_00225.

[21] Office of the Secretary of Defense, *Quadrennial Defense Review* (Washington, DC: Government Press of the United States of America, March 2014); President of the United States of America, *National Security Strategy of the United States of America* (Washington, DC: Government Press of the United States of America, December 2017); President of the United States of America, *National Security Strategy of the United States of America* (Washington, DC: Government Press of the United States of America, October 2022).

[22] Admittedly, some in the policy community have paid attention to the implications of climate change. See, for example, Chief of Naval Operations, The United States Navy, *Strategic Outlook for the Arctic* (Washington, DC: 2019); and "DOD, Other Agencies Release Climate Adaptation Progress Reports," U.S. Department of Defense, October 6, 2022, https://www.defense.gov/News/News-Stories/Article/Article/3182522/dod-other-agencies-release-climate-adaptation-progress-reports/.

[23] Halvard Buhaug, "Climate Change and Conflict: Taking Stock," *Peace Economics, Peace Science and Public Policy* 22, no. 4 (2016): 335, https://doi.org/10.1515/peps-2016-0034.

[24] Our analysis is a first step to study the effect of climate change on underwater acoustic propagation, and it is intended to investigate only whether climate change might have a significant effect. More detailed analyses are needed for deriving accurate predictions about specific conditions and locations.

[25] Busby, "Who Cares about the Weather?," 471.

[26] Stephen Biddle, *Military Power: Explaining Victory and Defeat in Modern Warfare* (Princeton, NJ: Princeton University Press, 2004), 36 and 55.

[27] On the challenges of camouflaging in the desert, see for example, Anthony H. Cordesman and Abraham R. Wagner, *The Lessons of Modern War: Volume 1: The Arab-Israeli Conflicts, 1973–1989* (Boulder, CO: Westview, 1991), 38.

[28] Simon Kingsley and Shaun Quegan, Understanding Radar Systems (Raleigh, NC: SciTech, 1999).

ence significant attenuation under extreme weather conditions.[29] Future research should explore the implications of these possible developments for military operations and warfighting in other domains.

Fourth, our results contribute to the academic, policy, and public debate on emerging technologies. According to some analysts and observers, the application of new technologies to underwater warfare is leading to ocean transparency, and, consequently, to the "end of the submarine as we know it."[30] Although people with real-world submarine or anti-submarine warfare operational experience, as well as analysts and scientists studying anti-submarine warfare operations, do not take the idea of transparent oceans seriously, this view carries significant weight among some academics, analysts, and journalists, and has also gained attention in mainstream newspapers and outlets. As a result, this topic warrants proper investigation. Our empirical analysis questions the view that submarine detection is going to become inevitably easier in the North Atlantic, and it raises some doubts when it comes to the Western Pacific. Whether we will enter an era of "ocean transparency" or return to an era of "ocean opaqueness" will ultimately depend on the relative magnitude of the effects of technological change vis-a-vis climate change. With this paper, we provide a first step to assess this debate which has, so far, ignored that the ocean is changing. Our analysis has important implications for countries such as the United Kingdom and France, which rely on ballistic-missile submarines for nuclear deterrence, among other things, and suggests that calls from analysts and pundits to cancel new submarine programs are unwarranted.

Fifth, our article suggests that, because of the different effects that climate change will have on the Atlantic and on the Pacific, the former might regain geostrategic relevance for Western allies. The increase in transmission loss that our oceanic acoustic models predict in the North Atlantic could give countries such as China and Russia a strategic advantage. Over the past decade, Russia has increased its submarine operations in the Atlantic, while China has put significant effort toward accessing the Atlantic through the Arctic Ocean.[31] The changes in underwater sound propagation that we identify could provide China or Russia with an incentive to further increase their submarine presence in the North Atlantic, with the goal of distracting their adversaries' anti-submarine warfare assets and resources away from other areas, such as the Western Pacific.

Climate Change in Security Studies Research

Climate change and technological change will have a great effect on countries, economies, and societies in the coming decades.[32] Academic research in international relations has tried to explore the implications of climate change and technological change for international politics. Existing works, however, have largely followed strict sub-disciplinary boundaries, which, in turn, has limited the breadth and reach of these investigations.

"Non-traditional" security studies scholars have looked at the negative effects of climate change on international peace and stability, with a focus on how it might erode access to critical resources and hence enhance the risk of conflict.[33] These works, however, have paid little attention to the implications of climate change for the military balance or military operations. Conversely, "traditional" security studies scholars have studied extensively the implications of technological change for international security, with a particular focus on how it might affect the military balance between countries.[34] These works, however,

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[29] Atmospheric attenuation (i.e., by haze, humidity, and rain) depends on the frequency of the electromagnetic pulse. David Lynch, Jr., *Introduction to RF Stealth* (Raleigh, NC: SciTech, 2004), 195-198.

[30] For a summary about the debate over the end of submarines, see, for example, Franz-Stefan Gady, "The End of the Submarine as We Know It?," *The Diplomat*, January 30, 2015, https://thediplomat.com/2015/01/the-end-of-the-submarine-as-we-know-it/.

[31] Magnus Nordenman, *The New Battle for the Atlantic: Emerging Naval Competition with Russia in the Far North* (Annapolis, MD: Naval Institute Press, 2019).

[32] Will Steffen et al., "The Trajectory of the Anthropocene: The Great Acceleration," *The Anthropocene Review* 2, no. 1 (January 2015): 81-98, http://dx.doi.org/10.1177/2053019614564785.

[33] For a summary, see for example, Cullen Hendrix, "Climate Change as An Unconventional Security Risk," *War on the Rocks*, October 23, 2020, https://warontherocks.com/2020/10/climate-change-as-an-unconventional-security-risk/; Elizabeth Mendenhall, et al., "Climate Change Increases the Risk of Fisheries Conflict," *Marine Policy* 117 (2020), https://doi.org/10.1016/j.marpol.2020.103954; Nina von Uexkull and Halvard Buhaug, "Security implications of Climate Change: A Decade of Scientific Progress," *Journal of Peace Research* 58, no. 1 (2021): 3-17, https://doi.org/10.1177/0022343320984210; Cody J. Schmidt et al., "Climate Bones of Contention: How Climate Change Influences Territorial, Maritime, and River Interstate Conflicts," *Journal of Peace Research* 58, no. 1 (2021): 132-150, https://doi.org/10.1177/0022343320973738.

[34] See, for example, Andrew S. Erickson, *Chinese Anti-Ship Ballistic Missile Development: Drivers, Trajectories, and Strategic Implications* (Washington, DC: Brookings Institution Press, 2016); Evan Braden Montgomery, "Contested Primacy in the Western Pacific: China's Rise and the Future of U.S. Power Projection," *International Security* 38, no. 4 (Spring 2014): 115–149, https://doi.org/10.1162/ISEC_a_00160; Clark, *The Emerging Era in Undersea Warfare*; Stephen Biddle and Ivan Oelrich, "Future Warfare in the Western Pacific: Chinese Antiaccess/Area Denial, U.S. AirSea Battle, and Command of the Commons in East Asia," *International Security* 41, no. 1. (Summer 2016): 7-48; Lieber and Press, "The New Era of Counterforce;" Michael Beckley, "The Emerging Military Balance in East Asia: How China's Neighbors Can Check Chinese Naval Expansion," *International Security* 42, no. 2 (Fall 2017): 78–119, https://doi.org/10.1162/ISEC_a_00294; and Eugene Gholz, "No Man's Sea: Implications for Strategy and Theory" (paper presented at the annual conference of the International Studies Association, 16–19 March 2016, Atlanta, GA).

have paid scant attention to climate change.[35]

According to "traditional" security studies, the military balance is the product of two main sets of factors: organizational capabilities and technological capabilities (the latter referring both to the quantity and quality of available military platforms). A critical assumption in these works is that the natural environment is constant. But if the natural environment changes, the military balance may change as well. In military operations, the natural environment plays a central role, providing opportunities for cover and concealment. In land warfare, hills, gullies, and vegetation provide soldiers with a natural cover from an enemy's firepower and with readily available means of concealment from an enemy's sensors.[36] Similarly, in air warfare, the curvature of the earth and the presence of a "super-refracting" duct in the atmosphere provide aircraft flying both at low altitude and at high altitude with the opportunity to limit detection by enemy ground-based radar.[37] In submarine warfare, surface ducts and shadow zones permit a submarine to avoid detection from an enemy's hull-mounted sonar.[38] Some environmental features — such as hills, the curvature of the earth, and undersea topography — are indeed constant. Others, however, are not, as they are the product of specific climatic conditions such as temperature, density, vapor, and salinity. When the natural environment changes, so too do some of the opportunities for cover and concealment. This is the focus of our article.

Climate change will affect international security and military operations in several ways. Rising sea levels, droughts, deforestation, extreme weather events, changing meteorological and seasonal patterns (e.g., the frequency and intensity of storms) will affect facilities, weapon systems, operations, and sensors. For instance, changes in sea levels might affect the viability and utility of some naval ports, whereas droughts and deforestation could make some military bases more difficult to service. Along the same lines, because of changing seasonal trends — getting winter weather in the spring or summer weather in the fall — as well as the higher frequency of extreme weather events, some military operations, such as amphibious operations, could become more difficult, and some military training and exercises less frequent, or limited in scope. Additionally, climate change could affect the performance or the maintenance cycle of ships, tanks, or aircraft. Rougher seas shorten the life cycle of propellers and shafts, whereas acidic waters and rains accelerate corrosion. Climate change could also affect sensors for data gathering, such as radar, laser, and sonar.

In this article, we focus on the influence of climate change on data gathering and data analytics. Because we live in the information age, the capacity to gather data through modern sensors and to analyze it correctly is of central importance. In warfare, real-time information that is accurate is a critical component of the long-range precision-strike complex, which requires the capability to detect, identify, track, and geolocate enemy platforms at long distances. Climate change might interfere with such capability. Deforestation, for example, could deprive ground forces of foliage and vegetation, which is a primary source of concealment outside of arctic and desert areas. Warming weather, on the contrary, might reduce the heightened effectiveness in winter months of thermal sensors. Extreme weather events, higher humidity, and higher temperatures, along the same lines, could negatively affect air and missile defense operations since some radar frequencies are more susceptible to weather interference. Similarly, changes in the oceanic environment could affect sonar performance. In the following sections we explain how this might happen.

Submarines and Anti-Submarine Warfare

Before discussing how an altered ocean environment could affect sonar detection, it is important to understand how submarines hide from and search for one another. The ocean is essentially opaque when it comes to the most effective sensors for detecting, identifying, and locating enemy assets on land or in the air, such as human sight, electro-optical sensors, infrared cameras, and radar systems. Submarines take advantage of this opacity to conceal their presence. For this reason, submarines are considered the "first 'stealthy' weapon system."[39] The capacity to hide underwater gives submarines a key advantage in military operations. Coastal submarines can be, under some circumstances, an effective means for deterring a much larger fleet from approaching an enemy's

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[35] Some works of "traditional security" studies have looked at resource competition in the Arctic because of climate change — see, for example, Jonathan N. Markowitz, *Perils of Plenty: Arctic Resource Competition and the Return of the Great Game* (Oxford, UK: Oxford University Press, 2020).

[36] Biddle, *Military Power*, 36.

[37] *Electronic Warfare Fundamentals* (Nellis Air Force Base, NV, 2000), 2.9-2.14 and 6.24, https://www.academia.edu/33372831/ELECTRONIC_WARFARE_FUNDAMENTALS_NOVEMBER_2000.

[38] Donald C. Daniel, *Anti-Submarine Warfare and Superpower Strategic Stability* (London: Macmillan Press, 1986), 1-11.

[39] Norman Friedman, *Submarine Design and Development* (Annapolis, MD: Naval Institute Press, 1984), 9.

shores.[40] Similarly, ballistic-missile submarines are widely considered the strongest leg of the nuclear triad because of the inherent difficulty of detecting and tracking them.[41] Attack submarines can also threaten an enemy's strategic lines of communications: They can be used to target commercial shipping in order to impose a naval blockade, as well as to silently pursue and threaten enemy military vessels, including coastal defense platforms like patrol boats and corvettes, and platforms for power projection like amphibious warships and aircraft carriers.[42]

In warfare, real-time information that is accurate is a critical component of the long-range precision-strike complex, which requires the capability to detect, identify, track, and geolocate enemy platforms at long distances. Climate change might interfere with such capability.

That submarines can hide underwater, however, does not mean they cannot be detected, identified, and tracked. The oceanic environment, as Leonardo da Vinci understood more than 500 years ago, facilitates the transmission of sound, sometimes at very long distances.[43] Since World War II, the detection of submarines has been conducted mainly through an acoustic technique: sonar.[44] Sonar does the equivalent thing in water that radar does in the air, with the difference being that the former takes advantage of acoustic waves whereas the latter exploits electromagnetic waves. Whereas electromagnetic waves can scan the aerial domain for hundreds or, under some conditions, thousands of kilometers, they can penetrate water from a few centimeters to just 100 meters (1 to 330 feet), a limitation that severely constrains their effectiveness for anti-submarine warfare. Acoustic waves, conversely, can propagate underwater for tens, hundreds or, under some conditions, even thousands of kilometers.[45]

Investments in underwater acoustics have coincided with investments in other assets, capabilities, and technologies. Most prominently, in the 1950s, the United States started deploying a network of fixed hydrophones (underwater microphones) at strategic points on the ocean floor, aimed at detecting the sound generated by Soviet submarines.[46] Over the following decades, U.S. capabilities increased significantly, to the point that the U.S. Navy could detect, identify, and locate Soviet submarines, and even "identify by hull number the identity of Soviet subs."[47] Since the 1970s, improvements in sensing technology and in signal processing have significantly enhanced the acuity and accuracy of passive sonar, as well as of active sonar.[48] Moreover, the increase in the type of available sensors across a broad range of anti-submarine warfare platforms — submarines, surface ships, rotary and fixed wing aircraft, and satellites — has further enhanced the likelihood of detecting submarines.[49]

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[40] Craig Hooper, "Export Subs: Simplicity Can Sell," NextNavy, last modified November 6, 2014, http://nextnavy.com/export-subs-simplicity-can-sell/.

[41] Owen R. Coté Jr., "The Trident and the Triad: Collecting the D-5 Dividend," *International Security* 16, no. 2 (1991): 117-45, https://doi.org/10.2307/2539062.

[42] See for example Thomas J. Christensen, "Posing Problems without Catching Up: China's Rise and Challenges for U.S. Security Policy," *International Security* 25, no. 4 (Spring 2001): 5-40, https://www.jstor.org/stable/3092132; Michael A. Glosny, "Strangulation from the Sea? A PRC Submarine Blockade of Taiwan," *International Security* 28, no. 4 (Spring 2004): 125-160, https://www.jstor.org/stable/4137451; and Biddle and Oelrich, "Future Warfare in the Western Pacific."

[43] Robert J. Urick, *Principles of Underwater Sound* (New York: McGraw-Hill, 1983), 2.

[44] Gary E. Weir, *An Ocean in Common: American Naval Officers, Scientists, and the Ocean Environment* (College Station, TX: Texas A&M University Press, 2001); and Jacob Darwin Hamblin, *Oceanographers and the Cold War: Disciples of Marine Science* (Seattle, WA: University of Washington Press, 2005).

[45] Ashley D. Waite, *Sonar for Practising Engineers*, third edition (Chichester, UK: Wiley, 2002), xxi-xxiii, 48-49.

[46] This system of hydrophones arrays is called the SOund SUrveillance System (SOSUS). Edward C. Whitman, "The 'Secret Weapon' of Undersea Surveillance," *Undersea Warfare* 7, no. 2 (Winter 2005); and Gary E. Weir, "The American Sound Surveillance System: Using the Ocean to Hunt Soviet Submarines, 1950-1961," *International Journal of Naval History* 5 no. 2 (August 2006), https://www.ijnhonline.org/wp-content/uploads/2012/01/article_weir_aug06.pdf.

[47] Ford and Rosenberg, *The Admirals' Advantage*, 105.

[48] Improvements in sensing technology allow modern sonar to pick up much weaker signals than in the past. See for example Thaddeus G. Bell, *Probing the Ocean for Submarines: A History of the AN/SQS-26 Long-Range, Echo-Ranging Sonar* (Los Altos Hills, CA: Peninsula Publishing, 2011), 129-170. Improvements in signal processing permit distinguishing a signal from a much noisier background — see Jim Bussert, "Computers Add New Effectiveness to SOSUS/CAESAR," *Defense Electronics*, October 1979, 59-64.

[49] Gordon D. Tyler, Jr., "The Emergence of Low-Frequency Active Acoustics as a Critical Antisubmarine Warfare Technology," *Johns Hopkins APL Technical Digest* 13, no. 1, (1992): 145–159, https://secwww.jhuapl.edu/techdigest/Content/techdigest/pdf/V13-N01/13-01-Tyler.pdf.

The use of sonar in anti-submarine warfare has led to a "hider-finder" competition between increasingly more effective detection technologies and increasingly quieter submarines.[50] Over the past 50 years, this competition has led to the development of new sensors for anti-submarine warfare, such as low-frequency active sonar, satellite-based and airborne synthetic-aperture radars that can detect the surface waves generated by a submarine moving underwater, sensors that can track oceanic flora reactions (biological luminescence) and thermal changes resulting from the passage of a submarine, laser technology capable of penetrating water beneath the sea surface (blue-green lasers), systems that can capture a submarine's interference with the earth's electromagnetic field (magnetic anomaly detector), probes that reveal the dispersal of contaminants in the ocean, and others.[51]

Yet, underwater acoustics remain the most important means for detecting enemy submarines. Most new non-acoustic sensors have inherent limitations, most notably by giving false alarms and having insufficient range, which means that even when fully operational, they cannot monitor large areas or deeper layers of the ocean for long-range detection.[52] Magnetic anomaly detectors, for instance, can cover up to 1,500 meters, which is still insufficient given the vastness of the ocean.[53] Satellite-based synthetic aperture radars, coupled with the dramatic increase in the number of satellites, offer a potential alternative system for persistent surveillance of the ocean. But their reach is still limited by the twin challenges of covering large areas of the ocean and detecting and correctly identifying small changes produced by submarines at depth. For this reason, in the foreseeable future, underwater sound propagation is reasonably going to remain a critical pillar of anti-submarine warfare. To appreciate the role of underwater acoustics, consider for instance that the Comprehensive Nuclear-Test-Ban Treaty Organization has only 11 hydro-acoustic stations compared to 170 seismic stations for global nuclear explosion monitoring. The difference has been explained by, among other things, the much longer range of underwater sound, which allows for long-range monitoring.[54]

Signal Processing, Submarine Detection, and Climate Change

In this section, we explain why climate change might affect the detection of hostile submarines, by introducing the basics of signal processing — that is, how a signal emitted (or reflected) by a submarine is distinguished from ambient noise. As we discuss below, both technological change and climate change affect signal processing. Existing work on the future of submarine warfare, however, have focused only on the former while neglecting the latter.

False Positives and False Negatives

Detecting enemy targets, whether in the air, on land, on the sea surface, or underwater, is one of the most important tasks for military organizations, for the very simple reason that you cannot defend yourself from what you cannot see. Detection is about distinguishing an object from its background. Conversely, military platforms operating in a hostile environment will try to conceal their presence or minimize the ways in which they differ from the background in which they are operating, i.e., camouflaging. Military platforms employ different types of concealment and camouflaging tactics to deceive different enemy sensors: using colored paint for visual sensors (human sight), employing cooling mechanisms for thermal sensors (such as infrared cameras), deflecting shapes for electromagnetic sensors (radar), and using quieting technology for passive acoustic sensors (sonar). The main problem for military systems tasked with detecting enemy targets is that sensors generally receive aggregate information that contains either only ambient noise, when the target is not present, or ambient noise and the signal generated by the target, when the target is

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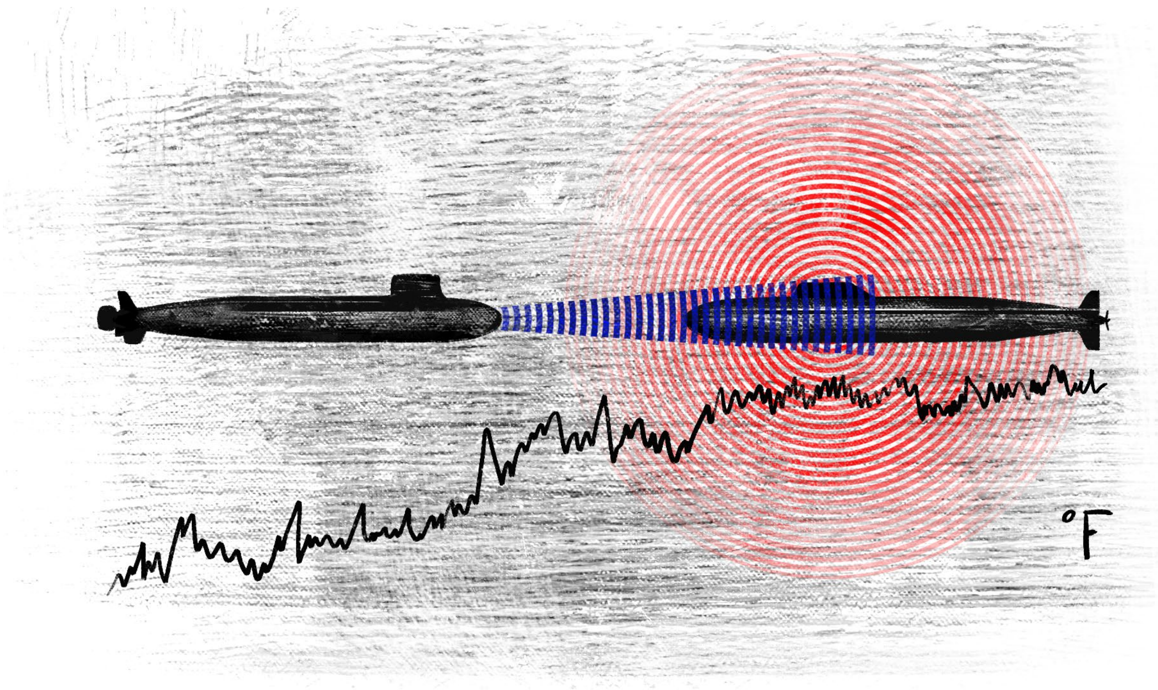
[50] Coté Jr., *The Third Battle*; Austin Long and Brendan Rittenhouse Green, "Stalking the Secure Second Strike: Intelligence, Counterforce, and Nuclear Strategy," *Journal of Strategic Studies* 38, no.1-2 (2015): 38-73, https://doi.org/10.1080/01402390.2014.958150. China has deployed its own "SOSUS" in the Western Pacific — see, for example, Lyle Goldstein and Shannon Knight, "Wired for Sound in the 'Near Seas': China Is Deploying an Ocean-Floor Surveillance Network To Strengthen Its Antisubmarine-Warfare Capability," *Proceedings* 140, no. 4 (April 2014), https://www.usni.org/magazines/proceedings/2014/april/wired-sound-near-seas; Joseph Trevithick, "China Reveals It Has Two Underwater Listening Devices within Range of Guam," *The Warzone*, June 30, 2019, https://www.twz.com/17903/china-reveals-it-has-two-underwater-listening-devices-within-range-of-guam.

[51] Daniel, *Anti-Submarine Warfare and Superpower Strategic Stability*, 36-49; Tom Stefanick, *Strategic Antisubmarine Warfare and Naval Strategy* (Lexington, MA: Lexington Books, 1987), 180-215; Daniel Gerald Daly, "A Limited Analysis of Some Nonacoustic Antisubmarine Warfare Systems" (master's thesis, Naval Postgraduate School, 1994), 17-35.

[52] There are some exceptions, such as satellite-based or airborne wake-detection systems, which, however, have other limitations. Daly, "A Limited Analysis of Some Nonacoustic Antisubmarine Warfare Systems."

[53] Newer anti-submarine warfare aircraft, such as the P-8 Poseidon, no longer carry magnetic anomaly detectors. Raymond McConoly, "P-8 Poseidon: The New Generation Submarine Hunter," *Naval Post*, July 21, 2021, https://navalpost.com/p-8-poseidon-the-submarine-hunter/.

[54] "The International Monitoring System," CTBTO Preparatory Commission, accessed February 15, 2024, https://www.ctbto.org/our-work/international-monitoring-system.



present.[55] Thus, detection requires distinguishing the signal from the noise. This is a statistical inference that is grounded in the very same mathematical principles that social scientists use to test hypotheses.[56]

Modern submarines, however, are very quiet and hence can be detected by passive sonar only at extremely short range. As a result, active sonars would generally yield longer detection ranges than passive sonars.

Given that both noise and signal fluctuate, they can be treated as two random variables.[57] Distinguishing the signal from the noise entails establishing whether, on average, the noise is statistically different from the signal.[58] In practice, because ambient noise is always present, detection requires identifying a threshold that is very unlikely to be crossed by ambient noise alone, but is very likely to be crossed by ambient noise *plus* the target's signal. When incoming sound crosses the detection threshold, the detection system rejects the null hypothesis that there is no target.[59] Since both noise and signal fluctuate, however, there are two inherent risks: the risk of a *miss*, and the risk of a *false alarm*. A miss occurs when the noise and the signal do not cross the detection threshold and the system incorrectly declares that a target is absent. This is equivalent to a false negative for social scientists. A false alarm occurs when the detection threshold is crossed because of ambient noise only, but the system incorrectly declares that a target is present. This is akin to a false positive for social scientists. Both the probability of a miss and the probability of a false alarm are a function of the detection threshold: The higher the detection threshold, the lower the likelihood of getting a false alarm, but the more

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[55] For simplicity, we use "finder" to describe the entity seeking a target and "hider" to that trying to avoid detection.

[56] See, for example, Douglas A. Abraham, "Signal Processing," in *Applied Underwater Acoustics*, eds. Leif Bjørnø et al., (Amsterdam, Netherlands: Elsevier, 2017), 743-807; and Douglas A. Abraham, *Underwater Acoustic Signal Processing: Modeling, Detection, and Estimation* (Cham, Switzerland: Springer, 2019), 307-346.

[57] Both noise and signal have a probability distribution (a mean and variance). Stefanick, *Strategic Antisubmarine Warfare*, 10.

[58] For the similarities and differences between signal processing for radar and sonar, see, for example, Francois Le Chevalier, *Principles of Radar and Sonar Signal Processing* (Boston, MA: Artech House, 2002).

[59] For an introduction, see William Kuperman and Philippe Roux, in *Springer Handbook of Acoustics*, ed. Thomas Rossing (New York, NY: Springer, 2014): 149-204, https://doi.org/10.1007/978-0-387-30425-0_5.

likely one is to get a miss. Conversely, the lower the detection threshold, the more likely one is to get a false alarm, but the less likely a miss.[60]

The Sonar Equation

There are two types of sonar: active and passive. Active sonar emits an acoustic pulse (a "ping") and captures its echo when the pulse is reflected after encountering an object. Passive sonar works like an ear: It captures sounds coming from the environment. Passive sonar allows for long-range detection by capturing low-frequency (5–500 hertz) sound radiated by noisy submarines ranging from ten to hundreds of kilometers away. Once an enemy submarine has been detected, the search will concentrate in a specific area where anti-submarine warfare assets may use active sonars to locate, identify, and track the target more precisely. Most active sonars emit a medium frequency (1000–10000 hertz) acoustic "ping" to capture the echo reflected by enemy submarines. In comparison to low-frequency sound, medium-frequency sound suffers more attenuation and thus has a shorter range. This limitation is coupled by the fact that the sound emitted by active sonar must travel twice as far — to and from — in comparison to sounds that are radiated by a submarine and detected by passive sonar. Modern submarines, however, are very quiet and hence can be detected by passive sonar only at extremely short range. As a result, active sonars would generally yield longer detection ranges than passive sonars.

Active sonar has one advantage in that the operator has control of the strength of the signal emitted (i.e., source level), which will be orders of magnitude larger than signals radiated by submarines. By emitting a ping, however, active sonar informs the hider that there is an active enemy seeker nearby. This is a particularly serious problem given that, assuming equivalent detection capabilities, the hider can hear the ping before the seeker hears the echo and detects the enemy.[61] In addition, active sonar generally emits medium-to-high frequency sound, which may experience greater weakening and hence may be more limited in terms of range.[62] Conversely, passive sonar aims to capture primarily low-frequency sound, and because it experiences much less attenuation, it could permit long-range detection, at least of noisy submarines. Passive sonar can also capture medium- and high-frequency sound, although it has a much shorter range of propagation.

The sonar equations are a basic tool for predicting the performance of existing sonar systems under selected conditions or for designing them to operate under desired conditions.[63] According to selected detection and false-alarm probabilities, the user determines the necessary signal-to-noise ratio to establish a detection, called Detection Threshold (DT).[64] The detection of a submarine by a passive sonar system will be successful if the following equation holds true:

$$SL - TL - NL + AG + PG \geq DT$$

In this equation, SL is the Source Level, which indicates the level of sound radiated by the target — how noisy the enemy submarine is. TL is the Transmission Loss, which indicates the loss of strength experienced by sound (i.e., attenuation) as it travels through the environment.[65] NL is the Noise Level, or the ambient noise in which the sonar operates. AG is the passive receiver's Array Gain (also known as Directivity Index, or DI), which quantifies the ability of the sonar receiver to distinguish between the signal and the noise by listening from a specific direction within a very small angle.[66] PG is the Processing Gain, which includes gains made possible through advanced signal processing technology. A submarine is detected when the sound it emits plus the capability of the passive sonar to discern sound along a specific direction plus the ability to discern the signal from the noise is greater than the transmission loss, plus the ambient and self-produced noise.[67]

Intuitively, while some of the terms of the sonar equation are substantially dictated by technological change, others are influenced by the surrounding oceanic environment, and therefore they can be im-

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[60] See online appendix at https://css.ethz.ch/content/dam/ethz/special-interest/gess/cis/center-for-securities-studies/pdfs/Appendix_Climate_Change_Military_Power.pdf.

[61] For this reason, as well as due to potential harm to marine animals, active sonar systems are typically used less than passive ones. For a discussion of active sonar, see Daniel, *Anti-Submarine Warfare and Superpower Strategic Stability*, 65-70.

[62] Over the past 30 years, however, improvements in technology have enabled the development of low-frequency active acoustics, which has a significantly longer range than high-frequency active sonar. Tyler, Jr., "The Emergence of Low-Frequency Active Acoustics," 147-151.

[63] All sonar equation terms are in dimensionless form and expressed using a logarithmic decibel scale. Leif Bjørnø and Micheal J. Buckingham, "General Characteristics of the Underwater Environment," in *Applied Underwater Acoustics*, eds. Leif Bjørnø, Thomas N. Neighbors III, and David Bradley (Amsterdam, Netherlands: Elsevier, 2017), 66-75.

[64] On signal-to-noise ratio, see Stefanick, *Strategic Antisubmarine Warfare*, 11-15; Norman Friedman, *U.S. Submarines Since 1945: An Illustrated History* (Annapolis, MD: Naval Institute Press, 1994), 65; and Le Chevalier, *Principles of Radar and Sonar Signal Processing*, 1-38.

[65] Some works call it Propagation Loss (PL). For a discussion, see Michael A. Ainslie and Christopher L. Morfey, "'Transmission Loss' and 'Propagation Loss' in Undersea Acoustics," *The Journal of the Acoustical Society of America* 118, no. 2 (August 2005): 603-604, https://doi.org/10.1121/1.1960170.

[66] For a discussion, see Alan B. Coppens and James V. Sanders, *An Introduction to The Sonar Equations with Applications* (Monterey, CA: Naval Postgraduate School, 1976), 74-77, https://apps.dtic.mil/sti/tr/pdf/ADA030034.pdf.

[67] See online appendix.

pacted by climate change. We discuss these factors in the following subsections.

How Technological Change Affects Sonar Detection

As mentioned above, technological changes impact sonar performance in two main ways: through improvements in quieting technology and through improvements in detection technology (including signal processing). These improvements affect four terms of the sonar equation: the source level, the array gain, the processing gain, and the detection threshold.

Advances in quieting technology decrease the source level, making detection harder.[68] Quieting technologies aim at lowering the noise radiated or reflected by a submarine.[69] Over the past 70 years, several improvements have made submarines significantly quieter: more hydrodynamic hull shapes, more complex geometries for propeller blades, larger numbers of blades on a propeller, advances in conventional propulsion systems, ducted nuclear-propulsion systems, and effective acoustic isolation techniques that minimize radiated noise or absorb or deflect incoming pings.[70] While further progress in quieting technology is possible, it is generally accepted that most of the main opportunities for noise reduction have been exploited, and additional improvements in quieting will deliver only marginal gains.[71] Some countries, however, have not yet caught up with the United States in terms of quieting technology, so there is reason to believe that they will try to reduce the radiated acoustic signals of their submarines in the future.[72]

Advances in detection technology lower the detection threshold and increase the array gain, thus making detection easier.[73] Detection technologies are the set of instruments and methods used to detect enemy submarines. Given that detection is about distinguishing between the signal radiated or reflected by the enemy submarine and ambient noise, to increase the chances of detection, the seeker needs to boost the received signal and minimize the incoming noise, i.e., increase the signal-to-noise ratio. In the realm of passive sonar, improvements can come from gathering and processing more data and from more effectively filtering out ambient noise. Having a larger sample of signals from a target will improve the knowledge of its acoustic signature, and thus further enhance the chance of future detection.[74] While in theory this is possible, in practice there is substantially no space for future relevant improvements in distinguishing at long range the signal radiated by a submarine from ambient noise, given the high level of quietness already reached by the most modern submarines and the observed increases of oceanic ambient noise.

As a result of these trends, according to some analysts and observers, technological change in the hider-finder competition will favor the finder and might even lead to the end of underwater stealth — to oceanic transparency.

Experts and observers expect that improvements in detection technology in the years ahead will compensate for those in quieting. These improvements will come from three main realms: a larger number of sensors (distributed sensors, multi-sensor connectivity, and surface and underwater autonomous vehicles), the resulting larger volume and greater diversity of data (“big data”), and more accurate analysis of data (i.e., digital signal processing and machine

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[68] Like stealth military aircraft, underwater stealth (i.e., quieting technology) reduces the range at which a submarine can be detected.

[69] Submarines emit two main types of noise, internal and external. Internal noise stems from machinery noise and personnel noise, such as speaking loudly or accidentally dropping objects. External noise stems from the turbulence created by the submarine as it cruises through water (flow noise) and by the rotation of the propeller (cavitation). External noise is a function of speed. For different types of noise of submarines, see Daniel, *Anti-Submarine Warfare and Superpower Strategic Stability*, 28-36; Friedman, *Submarine Design and Development*, 79; Waite, *Sonar for Practising Engineers*, 89-91; and David Blank et al., *Introduction to Naval Engineering – Second Edition* (Annapolis, MD: Naval Institute Press, 2005), 163.

[70] See online appendix.

[71] Stefanick, *Strategic Antisubmarine Warfare*, 173; Ralph E. Chatham, "A Quiet Revolution," *Proceedings* 110, no. 1 (January 1984), 41-46, https://www.usni.org/magazines/proceedings/1984/january/quiet-revolution. Anechoic coating offers a possible exception, which can further lower the submarine radiated noise as well as absorb incoming sound waves emitted by active sonar. See also online appendix.

[72] Andrew S. Erickson et al., "Underpowered: Chinese Conventional and Nuclear Naval Power and Propulsion," in *Chinese Naval Shipbuilding: An Ambitious and Uncertain Course*, ed. Andrew S. Erickson (Annapolis, MD: Naval Institute Press, 2016), 238-248.

[73] See online appendix.

[74] The principle is that if you know what you are looking for, you can more easily find it. The availability of acoustic signatures permits searching for signals at specific frequencies with very narrow bandwidths, substantially reducing (i.e., filtering out) the broadband ambient noise, thus enhancing the accuracy of sonar performance.

learning).[75] As a result of these trends, according to some analysts and observers, technological change in the hider-finder competition will favor the finder and might even lead to the end of underwater stealth — to oceanic transparency.[76] While this expectation is logically correct, it neglects concomitant changes in the ocean that are also affecting underwater sound propagation and detection. We discuss this aspect in the next subsection.

How Climate Change Is Affecting Sonar Detection

Climate change affects two aspects of the sonar equation: ambient noise and transmission loss, both of which could either increase or decrease. Ambient noise might increase in some areas due to more maritime traffic, while decreasing in other places because some marine species become extinct. An increase in ambient noise could mask the acoustic signals radiated by submarines. On the other hand, a decrease in ambient noise would lead to the opposite outcome. An increase in transmission loss means that the noise radiated or reflected by a submarine will experience greater attenuation, and hence the received signal received will be weaker. A decrease in transmission loss would have the opposite effect. In short, both stronger ambient noise and weaker signals contribute to a lower signal-to-noise ratio, which, in turn, will make detection more difficult, whereas lower ambient noise and stronger signals contribute to a higher signal-to-noise ratio, which, in turn, will make detection easier.

Climate change is affecting ambient noise in several ways. Ambient noise level is determined by natural phenomena such as waves, sea ice breaking, rain, and wind, as well as by human and animal activity, such as maritime traffic, natural resources exploration and exploitation, and marine life. Changes in the characteristics of waves, as well as rain and wind patterns, modify noise level locally, but at present are difficult to assess.[77] Along the same lines, the migration of marine species and shifts in maritime traffic and shipping routes due to climate change, although difficult to predict, could also affect noise level.[78] In some areas, ambient noise will likely increase, whereas in others it will likely decrease.[79]

Climate change is affecting transmission loss in several ways. Sound propagation is a function of water temperature, salinity, and depth.[80] Thus, by modifying temperature and salinity in the ocean, climate change will directly affect transmission loss.[81] Moreover, due to the increased absorption of carbon dioxide, some parts of the ocean are becoming more acidic, and acidity influences both transmission loss and ambient noise.[82] Finally, changes in both atmospheric and oceanic temperatures, precipitation regimes, and the rate of ice melting will modify patterns of sound propagation.[83]

It is important to stress that the impacts of climate change on transmission loss and ambient noise level vary and will continue to vary from area to area and thus should be interpreted as regionally site-specific.

Because the environmental conditions of the ocean directly affect underwater sound propagation, they also affect anti-submarine warfare. Consider, for instance, that in the northern and central parts of the South China Sea, the temperature and salinity of the water limit sound propagation and hence make submarine detection more difficult.[84] It follows that changes in temperature and salinity induced by climate change could alter existing conditions and thus make detection easier or harder. This is particularly the case because, in the decades ahead, the ocean is expected to experience significant transformations because of climate change.

The effects of climate change on the ocean are evident when we look at sea surface temperatures,

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[75] Moltz, "Submarine and Autonomous Vessel Proliferation;" Clark, *The Emerging Era in Undersea Warfare*; Brixey-Williams, "Prospects for Game-Changers in Detection Technology."

[76] Bradbury, "The Sub Story No One Wants to Hear."

[77] Ocean acidification causes a decrease in sound attenuation (and consequently in transmission loss) in deep waters, but at least for the next century its effect in the sonar equations can be considered negligible. See, for example, D. Benjamin Reeder and Ching-Sang Chiu, "Ocean Acidification and its Impact on Ocean Noise: Phenomenology and Analysis," *The Journal of the Acoustical Society of America* 128, no. 3 (2010):137-43, https://doi.org/10.1121/1.3431091; James F. Lynch et al., "Impacts of Ocean Warming on Acoustic Propagation Over Continental Shelf and Slope Regions," *Oceanography* 31, no. 2 (2018): 174–181, https://doi.org/10.5670/oceanog.2018.219.

[78] For example, a latitudinal shift of the Northern Atlantic storm track would cause a shift of the commercial shipping routes crossing the Northern Atlantic Ocean, with the goal of reducing the navigation risks and time.

[79] The level of ambient noise will likely increase in the Arctic Ocean in the future, already one of the quietest areas of the world ocean, because of sea ice melting and the consequent increase of maritime traffic, rain, wind, and wave breaking noise. Michael Ladegaard et al., "Soundscape and ambient noise levels of the Arctic waters around Greenland," *Scientific Reports* 11, no. 23360 (2021), https://doi.org/10.1038/s41598-021-02255-6.

[80] See online appendix.

[81] See online appendix.

[82] Scott C. Doney et al., "Ocean Acidification: A Critical Emerging Problem for the Ocean Sciences," *Oceanography* 22, no. 4 (2009): 16–25, https://doi.org/10.5670/oceanog.2009.93.

[83] See online appendix.

[84] Tong Zhao, *Tides of Change: China's Nuclear Ballistic Missile Submarines and Strategic Stability* (Washington, DC: Carnegie Endowment for International Peace, 2018), 31, https://carnegieendowment.org/2018/10/24/tides-of-change-china-s-nuclear-ballistic-missile-submarines-and-strategic-stability-pub-77490.

which are expected to increase up to 4°C over the next 80 years, in comparison to the baseline period (1961–1990).[85] Such increases in sea surface temperatures are relevant, because when it comes to underwater acoustic propagation, small variations in oceanographic conditions are sufficient to produce significant effects. The main factor determining underwater acoustic propagation is the speed of sound, which is approximately 1,500 meters per second in temperate and equatorial waters, with possible variations within the range of plus and minus 1 to 4 percent. Still, "[a]lthough these variations in the speed of sound are small, they have a profound effect on acoustic propagation in the ocean."[86] In fact, this limited variation in sound speed produces significant geographic, seasonal, weekly, and daily variations in the patterns of acoustic propagation.[87]

For instance, in the summer, surface waters are warmed in the afternoon in several ocean areas, causing the sound emitted by a source mounted on a ship's hull to bend downward and outside of the surface layer (the so-called sound surface duct), thus limiting the chance of detecting a relatively shallow submarine at long range — a phenomenon known as "afternoon effect."[88] Along the same lines, at low latitudes or in the summer season at mid-latitudes, solar heating warms up the upper layer of the ocean, which "does not support long-range sound propagation but instead gives rise to a deep acoustic shadow zone."[89] Accordingly, climate change might have a pronounced effect on anti-submarine warfare even if it produced only relatively limited changes in the ocean. Consider that small changes in signal-to-noise ratio are sufficient to significantly alter the probability of submarine detection.[90] For example, under some conditions, a decrease of only a few decibels in excess signal can shrink the probability of detection from 90 percent to 50 percent or decrease the range of detection by 50 percent.

Simulating the Effect of Climate Change

In this section, we explain how we studied the specific effects of climate change on underwater sound propagation. The ocean is a complex system that is continuously adapting and adjusting to new internal and external conditions.[91] In order to account for the relationship between different parameters that are highly non-linear, multi-variable, and influenced by feedback loops, we relied on numerical models providing oceanographic-acoustic simulations under different climate change scenarios.[92] For our investigation, we consider here two periods of time: a control period representing past climatic conditions and a treatment period representing possible future climatic conditions, assuming a significant rate of increase of greenhouse gases emissions.[93] In our simulations, we investigated the effects of climate change on both active and passive sonars. We consider a hypothetical scenario of friendly passive and active sonars searching for unfriendly submarines operating in the areas analyzed. For simplicity, we assume that the submarine is nuclear powered and thus does not have to resurface periodically.[94]

Parameters and Assumptions of Ocean-Acoustic Simulations

The dependent variable of our simulations is the transmission loss experienced by sound when travelling underwater. Transmission loss is the attenuation in intensity expressed in decibels between a given point and a reference distance. Transmission loss captures two different phenomena: the *regular weakening* of an acoustic signal as a result of range, as well as its *irregular weakening* due to the absorption of sound by seawater (attenuation), its scattering in different directions, and its diffraction toward the ocean bottom or toward the

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[85] See online appendix.

[86] Bjørnø and Buckingham, "General Characteristics of the Underwater Environment," 17.

[87] Coppens and Sanders, *An Introduction to The Sonar Equations with Applications*, 24; Urick, *Principles of Underwater Sound*, 118-120.

[88] Urick, *Principles of Underwater Sound*, 5 and 118.

[89] Bjørnø and Buckingham, "General Characteristics of the Underwater Environment," 66.

[90] Cox, *Sonar and Underwater Sounds*, 48; Urick, *Principles of Underwater Sound*, 388; and Abraham, *Underwater Acoustic Signal Processing*, 88-90.

[91] Rebecca Lewison et al., "Dynamic Ocean Management: Identifying the Critical Ingredients of Dynamic Approaches to Ocean Resource Management," *BioScience*, 65, no. 5 (May 2015): 486–498, https://doi.org/10.1093/biosci/biv018.

[92] For an introduction to underwater acoustic models, see for example, Paul C. Etter, *Underwater Acoustic Modeling and Simulation – fifth edition* (Boca Raton, FL: CRC Press, 2018).

[93] Rajendra K. Pachauri et al. (eds.), *Intergovernmental Panel on Climate Change, 2014: Climate Change 2014 — Synthesis Report. Contribution of Working Groups I, II, and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Geneva, Switzerland: IPCC, 2014).

[94] Unlike nuclear-powered submarines, conventional submarines must periodically resurface, making them easier to detect. See Friedman, *Submarine Design and Development*, 11; and Daly, "A Limited Analysis of Some Nonacoustic Antisubmarine Warfare Systems," 12.

ocean surface (with the creation of areas shielded from acoustic detection, so-called shadow zones).[95] For our simulations, we assume that the other variables of the sonar equation are constant.

We proceeded in three steps to determine transmission loss. First, we used data from an existing climatic model about the factors affecting sound propagation — water temperature and salinity — in the two periods under consideration.[96] To define temperature and salinity for the 2070–2099 period, we relied on the Representative Concentration Pathway 8.5, a "high greenhouse gas emission scenario" — a scenario in which there has not been "effective climate change mitigation policies, leading to continued and sustained growth in atmospheric greenhouse gas concentrations."[97] This scenario is not unrealistic, given that Western countries have failed to meet their own commitments set by the Kyoto (1997) and Paris (2015) agreements, and given that the industrialization of developing countries in Asia and Africa will lead to a further increase in greenhouse emission. Nevertheless, this is the worst-case scenario in climatic models used in periodic Intergovernmental Panel on Climate Change assessments. Since we are interested in investigating whether climate change will influence underwater sound propagation, and thus on submarine detection, we opted for a scenario that can help us to determine whether such a relationship exists.

Our interest is in assessing whether and how general patterns of sound propagation from the past could change in the future.

Second, using extracted data on temperature and salinity, we calculated the corresponding 30-year average sound speed for the two periods under consideration to determine the sound speed profiles for each geographic area we investigated.

Third, we used the BELLHOP acoustic model to calculate the transmission loss for the averaged sound speed profiles of the two periods, under different conditions that are relevant for submarine detection and identification.[98] By comparing the differences in average transmission loss between the two periods, we can observe the expected effect of climate change on underwater sound propagation — specifically, the effects of the changes in mean water temperature and salinity resulting from climate change.

The 30-year average period is a typical approach taken in climate studies to decouple climatic trends from short-term fluctuations, and a comparison after one century allows us to better demonstrate climatic trends. In this way, we aim to identify a possible background trend of transmission loss caused by climate change, keeping in mind that the transmission loss experienced during a real operation at a given time and place would be substantially different because of all the environmental factors involved.

We calculated our results in two ways: We calculated the 30-year average across 12 months (irrespective of seasonal variations), and then the 30-year average for the months of January and of July (to exclude seasonal variation). The results did not exhibit relevant differences between the cold and the warm season. Consequently, we examine a subset of the results below.

There are, of course, uncertainties concerning how the climate will evolve in the decades ahead. Our interest is in assessing whether and how general patterns of sound propagation from the past could change in the future. It is important to note that this is a conservative analysis because, by averaging out the short-term fluctuations, potential variations between past and future conditions are significantly reduced. Larger effects would be expected if we were to focus on very short time frames because of local and time variations in atmospheric and oceanographic phenomena affecting underwater sound propagation.

Deep Water Regions

In this study, we focus on deep water regions, oceanic areas where bottom depths reach more than 1,000 meters. Deep water regions are the most conducive to sound propagation for many reasons. First, the lack of obstacles permits sound waves to travel at longer distances with less reflection, absorption, or scattering by the seafloor. Second, mostly in low

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[95] Naval Oceanographic Office, *Fleet Oceanographic and Acoustic Reference Manual RP 33* (Stennis Space Center, MS: Naval Oceanographic Office, 1999), 8-18; Urick, *Principles of Underwater Sound*, 99-101.

[96] Enrico Scoccimarro et al., "Effects of Tropical Cyclones on Ocean Heat Transport in a High-Resolution Coupled General Circulation Model," *Journal of Climate* 24, no. 16 (August 2011): 4368-4384, https://www.jstor.org/stable/26191150.

[97] Keywan Riahi et al., "RCP 8.5—A Scenario of Comparatively High Greenhouse Gas Emissions," *Climatic Change* 109, no. 33 (2011), https://doi.org/10.1007/s10584-011-0149-y.

[98] Michael B. Porter and Homer P. Bucker, "Gaussian Beam Tracing for Computing Ocean Acoustic Fields," *The Journal of the Acoustical Society of America* 82, no. 4 (1987): 1349-1359; Michael B. Porter and Yong-Chun Liu, "Finite-Element Ray Tracing," in *Theoretical and Computational Acoustics – Vol. 2*, eds. Ding Lee and Martin H. Schultz (World Scientific Publishing Co., 1994), 956-957. See also online appendix.

and mid-latitude areas of the ocean, the ocean is divided into layers of varying water density and temperature. This vertical structure of sea temperatures generates a deep sound channel, an underwater area that is particularly conducive to sound propagation and which allows low frequency sound to travel for possibly thousands of kilometers.[99] Finally, acoustic detection in deep water regions is facilitated by the presence of so-called acoustic convergence zones, indirect channels of propagation which improve sonar performance for sonar operating close to the surface of the ocean.[100] This does not mean, however, that submarine detection is easy. Fronts between water masses with different features, internal waves, as well as rain, surface waves, and wind can complicate sonar detection in deep waters regions.[101]

We focus on three deep water regions in the North Atlantic and in the Western Pacific, respectively. For the North Atlantic, we analyze a high latitude area (Greenland Sea), a mid-latitude area (beyond the Bay of Biscay), and a subtropical area (near Tenerife). The first two sites have geostrategic relevance as they are submarine operating areas for Russia and NATO countries. The third area considers whether and how climate change will affect underwater sound propagation at lower latitudes. For the Western Pacific, we look at mid-latitude areas (the Sea of Japan), subtropical areas (the Philippine Sea), and tropical areas (the South China Sea). These areas are relevant for the current and future competition between Chinese, Japanese, South Korean, North Korean, and AUKUS (American, British, and Australian) submarines and anti-submarine warfare capabilities.[102] These areas are denoted by red circles in Figure 1.

Empirical Results

Our analysis indicates that sound propagation is going to experience a significant increase in transmission loss in the mid-latitude eastern North Atlantic (just beyond the Bay of Biscay), a moderate increase in transmission loss in the high latitude eastern North Atlantic (in the sea of Greenland) and in the mid-latitude Western Pacific (Sea of Japan), and a slight increase in transmission loss in the subtropical northern Western Pacific (Philippine Sea). This means that, in certain areas and under certain conditions, climate change could lower the probability of detecting submarines in the future, as well as shorten the range at which they can be detected. For submarines operating close to the surface in the Sea of Japan, however, we observe the opposite result: a decrease in transmission loss. This means that climate change could increase the probability and the range of detection of submarines whose depth of operation is limited (such as North

Figure 1. Areas Examined in the North Atlantic and Western Pacific

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[99] See online appendix.

[100] See online appendix.

[101] Naval Oceanographic Office, *Fleet Oceanographic and Acoustic Reference Manual*, 39-59. See also online appendix.

[102] Coté, Jr., The Third Battle; Nordenman, *The New Battle for the Atlantic.*

Korea's). The North Atlantic subtropical area (off Tenerife) and the Pacific tropical areas (South China Sea), conversely, do not exhibit any significant changes. We report the results of our simulations for these areas in an online appendix.

Passive Sonar: Transmission Loss

We start by investigating how climate change will affect passive sonar by comparing its performance in the two scenarios discussed above. We consider an underwater acoustic source representing a submarine that emits low frequency acoustic signals (100 hertz) and operates at 200–300 meter depths.

Figures 2a, 2b, 2c, and 2d show the transmission loss of a 100 hertz acoustic signal in the two periods of time in the four areas under examination.[103] By comparing the two time periods, we can identify how climate change might affect patterns of underwater sound propagation for each area.

The color scale in the figures indicates the transmission loss of the acoustic signal, expressed in decibels. The figures are a two-dimensional graphical representation of transmission loss and should be read from left to right. The signal source — the submarine — is on the upper left of the figure. Close to the source, the transmission loss is less than 60 decibels (red). As sound travels farther from the source (rightward and downward), the signal increasingly loses strength, losing up to 100 decibels (dark blue) or more. Dark blue means that, for a submarine emitting a signal between 90 and 100 decibels, all the acoustic signal radiated is lost, and thus the submarine cannot be detected. Pale light blue means that most of the signal has been lost and that the signal-to-noise ratio might not be sufficient for detection.

We observe the most significant change in underwater sound propagation between the two time periods in the mid-latitude North Atlantic, just beyond the Bay of Biscay.

To put these decibel levels in perspective, we can look to open sources about Soviet and Russian submarines, which might not be accurate but are still useful for understanding differences in magnitude. According to some open sources, for instance, Soviet nuclear-powered submarines in the 1970s and early 1980s were very noisy, radiating 150–170 decibels of low frequency acoustic sound in quiet patrol conditions and were therefore easy to detect by passive sonar. In the 1980s, Soviet submarines became much quieter, allegedly catching up with U.S. submarines in quietness (110–130 decibels). In the 2010s, Russian nuclear-powered submarines radiated about 110 decibels of acoustic signals, whereas American nuclear-powered submarines radiated about 95 decibels of acoustic signals. Chinese nuclear-powered submarines, conversely, are still much noisier at about 110–120 decibels. According to some open sources, diesel-electric submarines are generally much quieter, in some cases radiating as little as 70 decibels (Swedish and German submarines) and as much as 130 decibels in the case of the North Korean Romeo-class submarines.[104]

We observe the most significant change in underwater sound propagation between the two time periods in the mid-latitude North Atlantic, just beyond the Bay of Biscay (Figure 2a). In the 1970–99 period, we observe two main patterns of sound propagation. First, we have *direct* propagation: In the upper part of the graph (less than 200 meters deep), the sound is trapped in an upper layer sound channel leading it to travel a long distance with little transmission loss. Second, we have *indirect* sound propagation: The V-shaped arcs — forming convergence zones near the sea surface, where acoustic energy concentrates — show the sound refracting from the source downward to more than 3 kilometers in depth and then upward toward the surface, permitting long-range detection as long as there is a sonar receiver located in the convergence zone at the time the signal passes so that the sonar can capture the acoustic signal.

In the 2070–2099 period, we observe a significant increase in transmission loss in the North Atlantic. The sound channeling close to the ocean surface disappears. As a result, it is no longer possible for a passive sonar operating in the upper water layer (0–500 meters deep) to detect, through direct propagation, an enemy submarine operating at 200 meters at long distance. Sound does still propagate, forming convergence zones. Yet, for these signals to be detected, a passive sonar would need to be in the convergence zone itself. Moreover, compared to the 1970–99 period, the convergence zone progressively expands in width, and thus is less intense. The detection of the sound propagating through convergence zones

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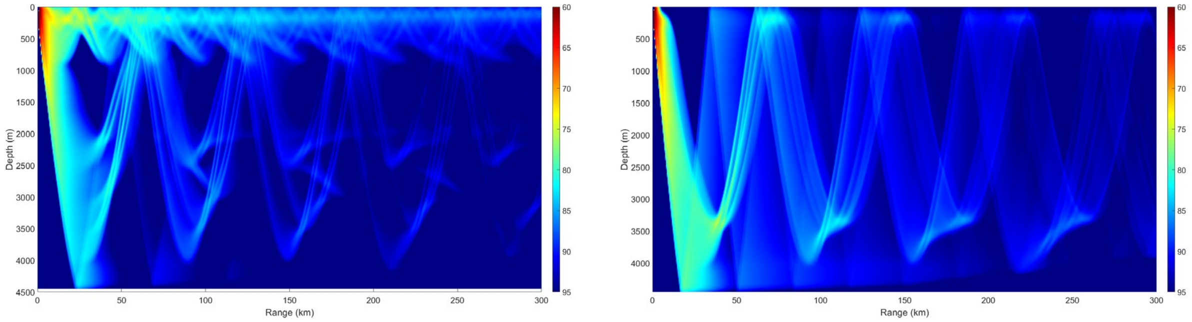
[103] The results shown in Fig. 2 are valid also for acoustic transmission loss of signals emitted by a low frequency active sonar (doubling the values to account for the return path of the reflected signal).

[104] The acoustic signal radiated by submarines is partly dependent on cruising speed (caused by turbulence and rotating propellers) and partly independent (caused by machinery and personnel). See online appendix.

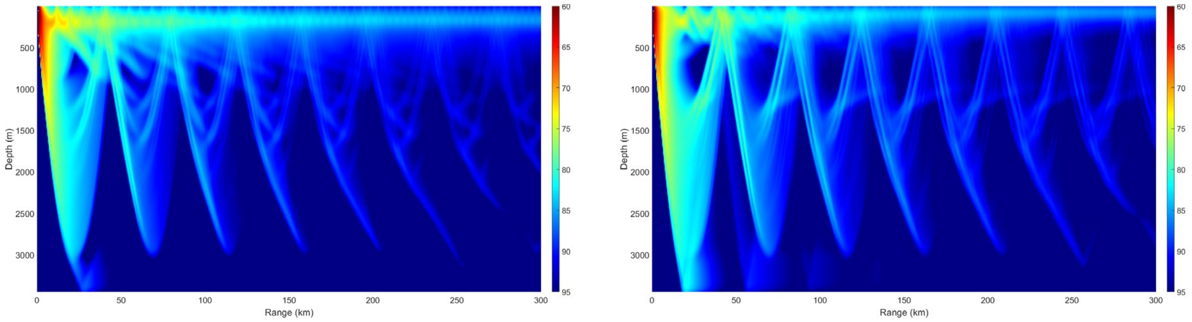
Variation in Transmission Loss (decibels) for Passive Sonar



1970-1999

2070-2099

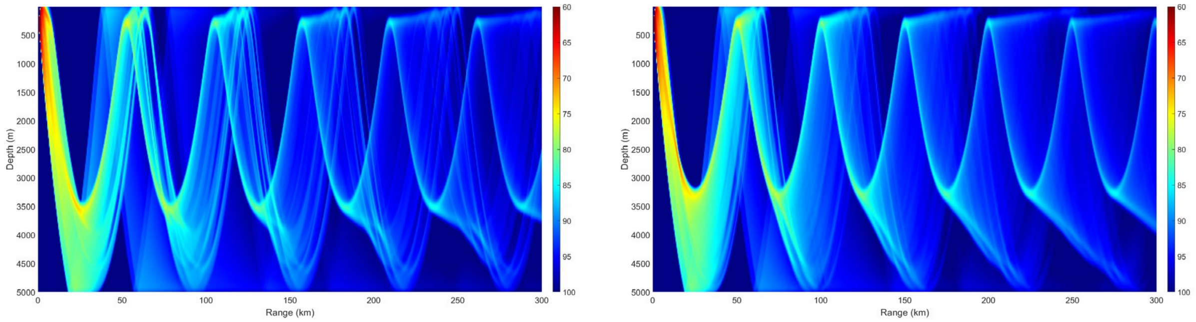
Figure 2a: North Atlantic (100 hertz, source at 200 meters)



1970-1999

2070-2099

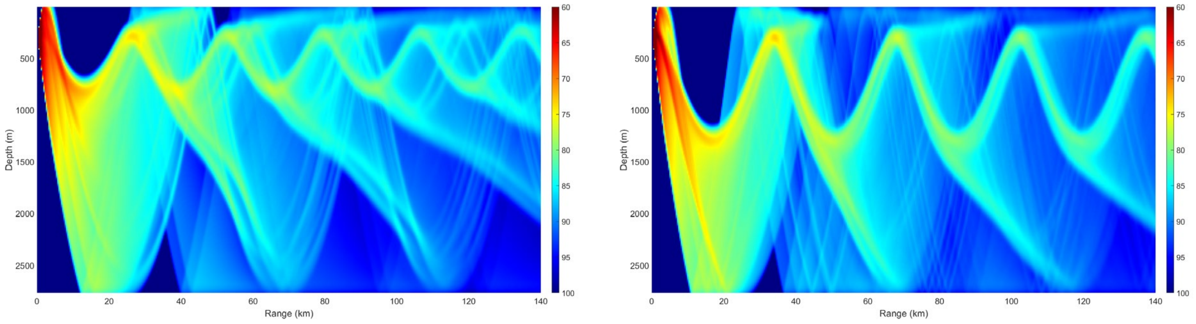
Figure 2b: Greenland Sea (100 hertz, source at 200 meters)



1970-1999

2070-2099

Figure 2c: Philippine Sea (100 hertz, source at 300 meters)



1970-1999

2070-2099

Figure 2d: Sea of Japan (100 hertz, source at 300 meters) will most likely be at 60–80 kilometers and perhaps at 140–150 kilometers, but unlikely between those depths or deeper than 150 kilometers.

In the Greenland Sea (Figure 2b), we observe an increase in transmission loss between the 1970–1999 and the 2070–2099 periods, although it is more moderate than in the mid-latitude eastern North Atlantic region. The surface duct, which improved acoustic propagation in the past, becomes weaker in the future, as reflected by the fainter light-blue horizontal line in the upper layer of the ocean (0–200 meters deep). Such a weak surface duct, however, is unlikely to help long-range detection of quiet submarines, as most of the signal will have been lost after 150 or 200 kilometers.

In the Philippine Sea (Figure 2c), we observe only minor changes between the past and the future. The pattern of underwater sound propagation does not vary — there is no direct propagation either in the past or in the future. There is only indirect propagation through convergence zones. These convergence zones become more uniform in the future scenario. However, based on these graphs, we cannot identify any substantive changes.

Similarly, in the Sea of Japan (Figure 2d), we observe only minor variations between the past and the future. The pattern of underwater sound propagation remains constant. We observe no direct propagation either in the past or in the future. Instead, we observe only indirect propagation through the convergence zones. However, these convergence zones are deeper in the future scenario, making detection by sonar in the upper layer of the ocean more difficult.[105]

We employ an additional method that considers the variable depths at which submarines operate to assess the change more accurately in transmission loss in these geographic areas.

Passive Sonar: Detection Ranges

In the previous section, we described the results obtained by considering submarines navigating at 200 meters (Atlantic sector) and 300 meters (Pacific sector). Patterns of underwater sound propagation, however, can vary depending on the depth at which a submarine operates. In a real operational scenario, a submarine will choose a depth at which sonar detection is more difficult, based on both climatological and observable data. Most submarines operate in the upper layer of the ocean, from 400 to 500 meters deep to near the surface. In this section, we consider a submarine at different depths, spanning from 10 to 490 meters with depth intervals of 20 meters.

We performed additional acoustic simulations to assess the potential changes in the detection range of passive sonar. Specifically, with our simulation we considered the maximum transmission loss that a sonar system can tolerate, while still being able to detect a submarine.[106] This maximum transmission loss is called the figure of merit (FOM), which is a quantitative measure of the sonar performance.[107] In practical terms, the larger the figure of merit, the better the sonar will perform.[108]

To calculate the maximum detection range of the sonar, we set a figure of merit of 80 decibels. This is representative of multiple cases, such as a well-performing sonar searching for either a quiet submarine in a relativity quiet environment or a noisy submarine in a relatively noisy environment. It considers a number of depths for both the submarine and the sonar. We calculate detection ranges for both direct and indirect acoustic propagation.[109] Our results using this figure of merit for passive sonar are identical for direct and indirect propagation. We have focused on submarines operating at some representative depths (100, 200, and 300 meters), and our results derive from 30-year averages in the month of January (to eliminate seasonal variation).[110] Because we focused on a relatively quiet submarine, the ranges at which it can be detected do not reach the several hundred kilometers of the early Soviet nuclear submarines.

> **Because of the oceanographic conditions in the Pacific areas that we examined, the detection ranges are much shorter than in the Atlantic.**

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[105] For the Sea of Japan, the graph is limited to a range of 140 kilometers because of the shape of the sea.

[106] Specifically, we calculated the maximum transmission loss for a probability of detection of 50 percent.

[107] See online appendix.

[108] Urick, *Principles of Underwater Sound*, 407-408; Abraham, *Underwater Acoustic Signal Processing*, 90-91; Etter, *Underwater Acoustic Modeling and Simulation*, 67, 427-430; and Richard P. Hodges, *Underwater Acoustics Analysis, Design and Performance of Sonar* (Chichester, UK: Wiley, 2010), 283-289.

[109] Direct propagation refers to the distance from the submarine to the sonar along which the transmission loss is always lower than the chosen figure of merit, whereas indirect propagation refers to the maximum distance at which the submarine can be detected due to surface and bottom bouncing of acoustic rays and acoustic convergence zones.

[110] See the online appendix to view the results of the simulations in graph form.

Near the Bay of Biscay, we observe changes in maximum detection range between the past and the future scenario. For a submarine at 100 meters deep and a sonar in the upper layer of the ocean (0–200 meters deep), our simulations suggest that the maximum detection range could increase from about 10 kilometers in the 1970–1999 period up to almost 100 kilometers in 2070–2099. With a submarine located at greater depths (200 meters and 300 meters), the situation reverses: Maximum detection ranges shrink from 60 kilometers and 35 kilometers, respectively, to less than 20 kilometers for both depths. Given this increase in detection range, a submarine would likely choose to stay deeper, making it significantly harder to detect than in the past. Conversely, the submarine would be more vulnerable when it operates near the surface to communicate or conduct other operations.

In the Greenland Sea, we observe more consistent variations among the three examined submarine depths: Maximum detection ranges decrease significantly, more than halving in the case of a submarine at 300 meters deep, from 60 kilometers in the past to slightly more than 20 kilometers in the future.

In the Western Pacific, the magnitude of the change is much more moderate. Because of the oceanographic conditions in the Pacific areas that we examined, the detection ranges are much shorter than in the Atlantic. In the Philippine Sea, detection ranges further decrease at all depths. Even though this reduction is very limited in absolute value (e.g., from 10 kilometers to 7 kilometers), it is still relevant in relative terms (in the order of 20–30 percent). We also observe a slight reduction in the detection range in the Sea of Japan, except for a submarine cruising at 100 meters and a passive sonar located at around 100 meters deep. In this case, the detection range increases from 10 kilometers in the past to about 45 kilometers in the future. This is a key finding, considering the limitations of North Korea's submarines, which are very noisy and inevitably constrained in terms of depth of operation.[111]

Active Sonar: Transmission Loss

We repeated the previous two analyses but applied them to the performance of active sonar. After a submarine has been detected at long range by passive sonar or by other means, anti-submarine warfare shifts to using active sonar to search for the submarine. Active sonar, as explained above, scans the ocean by emitting medium frequency sound and capturing its echo after it is reflected by an object, with the goal of accurately detecting and geolocating a possible target, as well as identifying its direction and speed of motion. The acoustic signal emitted by an active sonar, although many orders of magnitude louder than the signal radiated by submarines, will need to travel two ways.[112] When looking at the graphs depicting our results, one should keep in mind that they show only one-way transmission loss. Consequently, the values of transmission loss shown must be doubled to account for that the signal reflected by the submarine must travel back to the sonar.[113]

For our analysis, we consider a mid-frequency (2,000 hertz) sound signal emitted by a source at depths ranging from 100 meters to 200 meters. This is representative of several types of sonar, such as variable depth sonar, which is towed by ships or dropped by helicopters, as well as by sonar mounted on the bow of submarines. This latter type of sonar is rarely used, however, because by emitting a "ping" a submarine would give up its position, and hence lose its stealth advantage. When comparing the results of these acoustic simulations, we observed significant variations in patterns of underwater acoustic propagations between the 1970–1999 and 2070–2099 periods (Figures 3a, 3b, 3c, and 3d). The most significant changes appear in the eastern North Atlantic (beyond the Bay of Biscay). We observe more moderate changes in the Greenland Sea and in the Sea of Japan. The Philippine Sea, on the other hand, experiences relatively little change.

In the eastern North Atlantic, for the 1970–1999 period, we observe a surface duct between 50 and 100 meters that favors direct acoustic propagation, and convergence zones that permit quite good indirect acoustic propagation at depths greater than 100 meters. For the 2070–2099 scenario, we observe that the shadow zone, the dark blue area between sound rays that cannot be penetrated by acoustic pings, has become significantly larger than in the past. As a result, it becomes particularly difficult to detect submarines that are below 150–200 meters and that are 10 kilometers to 40 kilometers away from the active sonar — depths and distances that are within reach of an active sonar under other conditions.

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[111] Joseph S. Bermudez, Jr., "North Korea: Test Stand for Vertical Launch of Sea-Based Ballistic Missiles Spotted," *38 North*, October 28, 2014, https://www.38north.org/2014/10/jbermudez102814/; H. I. Sutton, "ROMEO-Mod Submarine," *Covert Shores*, July 23, 2019, http://www.hisutton.com/ROMEO-Mod_Submarine.html; Guy Taylor, "North Korea Secretly Building Nuclear Submarine: Report," *Washington Times*, September 17, 2017, https://www.washingtontimes.com/news/2017/sep/17/report-north-korea-secretly-building-nuclear-subma/; and Agence France-Press, "Despite progress, North Korea submarine missiles not ready until 2018 at earliest, say experts," *South China Morning Post*, August 27, 2016, https://www.scmp.com/news/asia/east-asia/article/2009860/despite-progress-north-korea-submarine-missiles-not-ready-until.

[112] An active sonar can emit as much as 200–235 decibels.

[113] In addition, the target strength — the amount of acoustic energy reflected by the submarine, which varies according to several factors related to the submarine itself — would need to be considered in the sonar equation, modified for active sonar systems. Yet, as we are focused on the effects of climate change on acoustic transmission loss, we assumed a Target Strength of 0 decibels.

There are two factors causing this larger shadow zone. First, we observe a much stronger surface duct in the first 150 meters of the water column. Sound emitted by active sonar will be trapped in this sound duct and will experience significant transmission loss when exiting and propagating outside of the duct itself. This surface duct, thus, facilitates the detection of submarines that operate in the duct, but it makes it much more difficult to detect submarines that cruise below 150–200 meters, in the shadow zone. Second, the arc of the convergence zones expands — close to the surface, from 25 kilometers in the 1970–1999 period to 60 kilometers in the 2070–2099 period — and experiences significant weakening. Given that active sonar involves a two-way transmission, such an increase in the arc of the convergence zone and an increase in transmission loss could reduce the effectiveness of actively scanning the ocean.[114]

In the Greenland Sea, we observe a more moderate change: Compared to the past, much more acoustic energy travels toward the bottom of the ocean and is lost, and the surface duct gets closer to the surface and becomes much weaker. In the Philippine Sea, there are barely any discernible changes between the past and future scenarios. In the Sea of Japan, more acoustic energy is deflected toward the sea floor, which entails more absorption and hence more transmission loss. As a result, the arcs of the convergence zones expand significantly both in depth and in width, reaching a depth of 2,200 meters in comparison to 1,200 meters in the past, which might interfere with detection beyond 45 kilometers.

Active Sonar: Detection Ranges

As we did for passive sonar, we ran an additional acoustic simulation for active sonar as a robustness test. This test is aimed at determining the maximum detection range of an active sonar. Unlike for passive sonar, in the case of active sonar the results for direct propagation and indirect propagation differed and so we discuss both.[115] We discuss the results obtained considering a maximum transmission loss (figure of merit) of 160 decibels.[116]

In the case of active sonar, we observe the most significant changes beyond the Bay of Biscay (for both direct and indirect propagation) and more moderate changes in the other areas. In the Bay of Biscay, we observe a drastic reduction of maximum detection ranges, except in the case of a submarine located at 100 meters with a sonar operating to a maximum depth of 130 meters for direct propagation and 200 meters for indirect propagation. As observed for passive sonar, under these conditions a submarine would likely cruise deeper, which would make enemy detection more difficult than in the past. In the Greenland Sea, maximum detection ranges with direct propagation decrease up to 50 percent for a submarine located at 100 or 200 meters. For direct propagation at 300 meters, or for indirect propagation at different depths, we did not observe relevant variations between the future scenario and the past. In the Philippine Sea, the already short detection ranges for direct propagation are further reduced. In the case of direct propagation, the variation is limited to a couple of kilometers, in absolute values, but accounts for about 20 percent or more in relative terms. There is no substantial change when it comes to indirect propagation. In the Sea of Japan, differences are less significant for direct propagation, with a general tendency toward a decrease of detection ranges of a couple of kilometers, although this represents a decrease of up to 50 percent in relative terms. For indirect propagation, we observe a greater decrease in the detection range, in some instances up to 35 kilometers — a decrease of up to 90 percent in relative terms.

> **This result is intuitive: Waters are warmed from the top, thus, in a warming climate, acoustic rays bend further downward, thus reducing the sonar detection ranges.**

A common feature to every area analyzed, especially in the case of a submarine at 200 and 300 meters deep, is the loss of detection range for sensors close to the sea surface. This change will affect the performance of hull-mounted active sonars. This result is intuitive: Waters are warmed from the top, thus, in a warming climate, acoustic rays bend further downward, thus reducing the sonar detection ranges.

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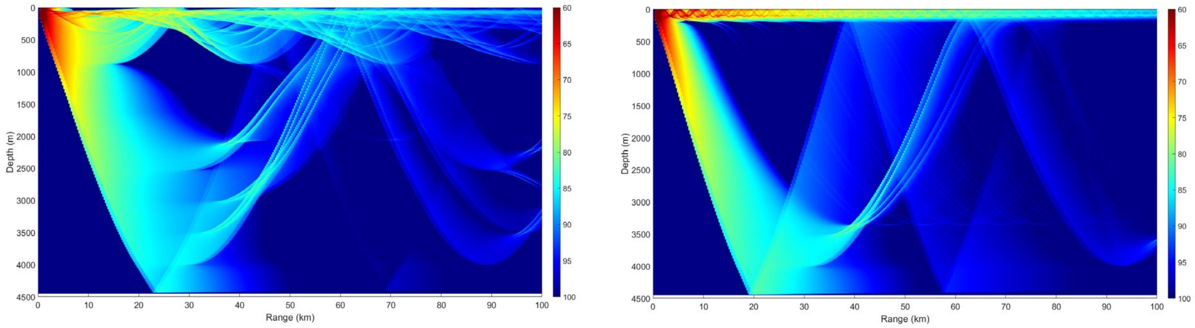
[114] Waite, *Sonar for Practising Engineers*, 56.

[115] Direct propagation refers to the horizontal spreading of sound outward, whereas indirect propagation refers to the propagation of sound through convergence zones.

[116] From the Active Sonar Equation: SL - 2TL + TS = NL - AG +PG + DT where TS is the Target Strength. In this case, FOM = SL + AG + PG +TS – (NL + DT) where TS is assumed equal to zero. The sonar operator can select SL within the power range of the system. To see the results of these simulations in graph form, please see the online appendix.

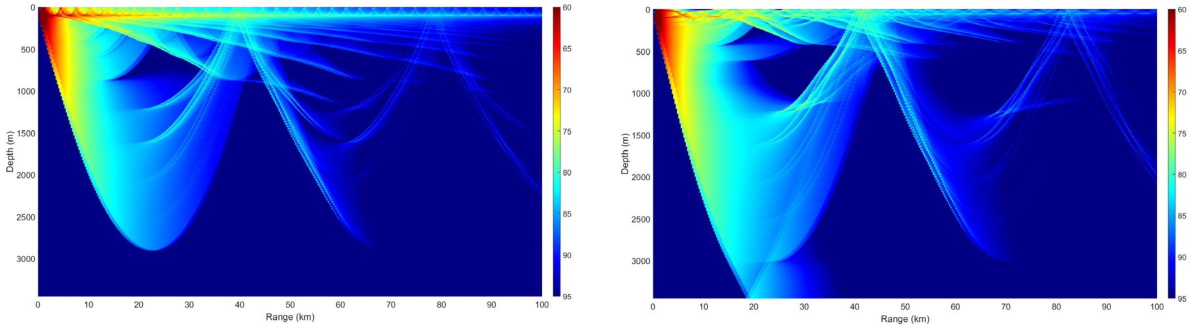
Variation in Transmission Loss (decibels) for Active Sonar



1970-1999

2070-2099

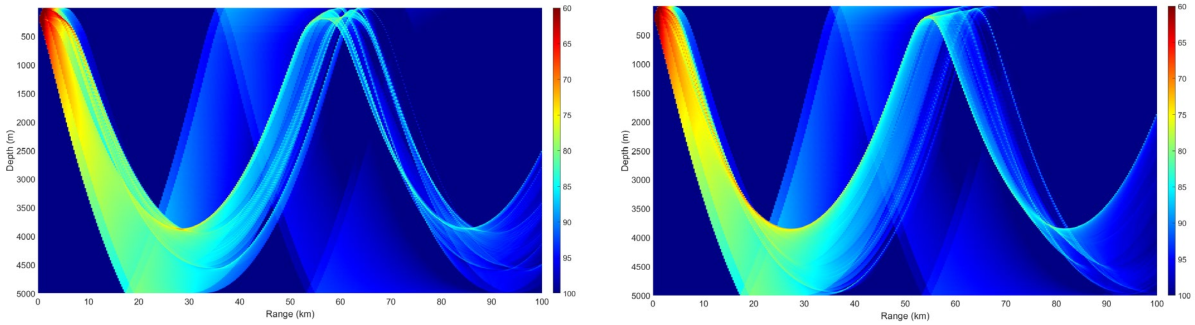
Figure 3a: North Atlantic (2,000 hertz, source at 100 meters)



1970-1999

2070-2099

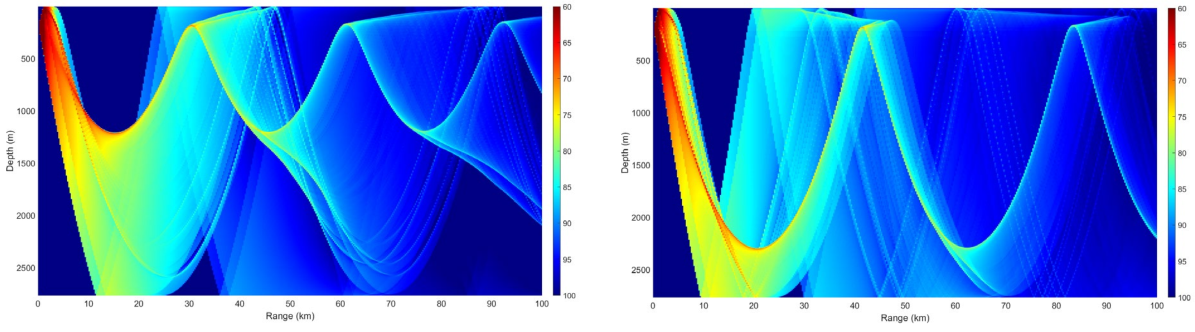
Figure 3b: Greenland Sea (2,000 hertz, source at 100 meters)



1970-1999

2070-2099

Figure 3c: Philippine Sea (2,000 hertz, source at 200 meters)



1970-1999

2070-2099

Figure 3d: Sea of Japan (2,000 hertz, source at 200 meters)

Limitations

The results of our ocean acoustic simulations suffer from the inherent limitation of all simulations — they are dependent on the assumptions of their underlying models. Our simulations assume that other variables in the sonar equation, such as noise level, signal strength, and detection threshold, are constant. Admittedly, these variables are also likely to change due to an increase in sea traffic as well as improvements in detection and quieting technologies.

Over the next 50 to 80 years, ambient noise from maritime traffic, which has a low frequency similar to the frequency emitted by submarines, will very likely increase and hence could make detection more difficult.[117] Over the same period, quieting technology is also likely to improve, including better acoustic isolation of the hull, the application of anechoic coating, the replacement of propellers with propulsors, the increasing adoption of air-independent propulsion submarines, the development of quiet cooling systems for nuclear reactors, and new deflecting-shaped hulls. These advances promise to deliver quieter submarines that will prove even more difficult to detect than the already very quiet Russian submarines.[118] However, detection technologies will also inevitably improve, because of developments in sensor acuity, multi-sensor connectivity, big data, and machine learning. Because of the very nature of these changes, and the fact that they may impact transmission loss positively or negatively, it is not possible to determine what their aggregate effect on submarine detection will be. Our analysis aims at showing only that climate change is going to influence a key variable of the sonar equation, transmission loss.

Our analysis relies on an additional, implicit assumption: that acoustic detection is going to remain a key pillar of anti-submarine warfare in the decades ahead. Even though this is a reasonable assumption, at least for active sonar, it should not be taken for granted. Modern submarines are very quiet and have already diminished the critical role of passive sonar. Other advances might further strengthen this trend, and non-acoustic detection systems might replace underwater acoustics to a significant degree. Because of this, some considerations are warranted.

To start, we want to stress that our analysis aims only at comparing trends in the past with possible trends in the future. The relevance of underwater acoustics is unlikely to disappear in the next 20 to 30 years, thus our analysis and its substantive implications are still relevant for the medium term, even if, toward the end of the century, the underwater acoustics discipline is no longer as useful. Moreover, with our focus on underwater acoustics, we have been able to investigate the variation across time of a variable that can be estimated, transmission loss, to compare the past with the future. With other technologies, such an analysis would not be possible to such a degree of granularity. In this regard, it is important to emphasize that our analysis is limited to active and passive sonar, and our results are not informative about other realms. Our findings, however, point to the possibility that climate change could influence other non-acoustic detection technologies, such as those that capture bioluminescence and thermal scarring.

Biological luminescence, or bioluminescence, is the production and emission of light by living organisms, which can be exploited in order to identify the presence of a submarine — take, for example, plankton illuminating in response to a passing submarine.[119] Because of the growing availability of sensors and data, bioluminescence promises to become an important asset in underwater detection.[120] Yet, if climate change causes some marine species to behave differently, to migrate to waters with more nutrients, or to become extinct, the parameters used may no longer be reliable or useful, thus diminishing the promise of this new means of detection.[121]

Thermal scarring denotes changes in ocean water temperature caused by a submarine, which can heat surrounding waters or displace colder waters toward the sea surface.[122] Tracking these changes in tem-

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[117] Filters that automatically screen out sound at specific frequencies that are of no interest increase the chances of detection by reducing noise and hence increasing the signal-to-noise ratio.

[118] Improvements for quieting are limited by the physics of acoustics and decreasing marginal returns. Yet, adversaries of the United States, such as Russia and China, still lag behind, which leaves space for quieter submarines. See, for example, Matt Korda, "ICBM Advocates Say US Missile Subs Are Vulnerable. It Isn't True," *DefenseOne*, December 10, 2020, https://www.defenseone.com/ideas/2020/12/icbm-advocates-say-us-missile-subs-are-vulnerable-it-isnt-true/170677/. On deflecting-shaped hulls, see H.I. Sutton, "Radical New Stealth Submarine, Type-212CD, Will Be Much Larger," *Naval News*, September 14, 2021, https://www.navalnews.com/naval-news/2021/09/radical-new-stealth-submarine-type-212cd-will-be-much-larger/.

[119] Jon Copley and Duncan Graham-Rowe, "The Cold War Resurfaces," *The New Scientist*, November 20, 1999, https://www.newscientist.com/article/mg16422130-200-the-cold-war-resurfaces/. For an example of bioluminescence applied to Anti-Submarine Warfare, see, for example Mark Denny, *Blip, Ping & Buzz: Making Sense of Radar and Sonar* (Baltimore, MD: The Johns Hopkins University Press, 2008), 57.

[120] Sarah Laskow, "How the Navy Tried to Turn Bioluminescence Against the Soviets: They spent decades on it," *Atlas Obscura*, January 13, 2017, https://www.atlasobscura.com/articles/how-the-navy-tried-to-turn-bioluminescence-against-the-soviets; Grant Turnbull, "Unlikely Spies: Using Marine Organisms as Underwater Sensors," *Naval Technology*, October 16, 2019, https://www.naval-technology.com/features/unlikely-spies-using-marine-organisms-as-underwater-sensors/.

[121] Jeremy Wilks, "Fish Are Swimming to Cooler Waters as Climate Change Heats Our Oceans," EuroNews, accessed February 9, 2024, https://www.euronews.com/green/2021/06/14/how-fish-are-swimming-to-cooler-waters-as-climate-change-heats-our-oceans.

[122] Copley and Graham-Rowe, "The Cold War Resurfaces."

perature, however, will likely become less effective in some areas, as the general warming of the upper layer of the ocean could reduce the thermal signature left by submarines. Conversely, in some areas, where the upper layer of the ocean will become colder (e.g., because of melting ice), the thermal signature left by submarines might become sharper.

Discussion

In this paper, we investigated the effects of climate change on military power, by looking at the specific case of anti-submarine warfare. Scholars that have studied climate security have primarily focused their attention on resource scarcity and how it might increase the risks of conflict. However, they have not explored how climate change will affect military capabilities and operations.[123] Conversely, traditional security studies scholarship has either explored these questions only tangentially or neglected them altogether. This literature has studied the factors that affect competition among great powers and strategic stability, such as technological changes and organizational adaptation. Yet, for the most part, it has neglected climate change, assuming that the natural environment is constant. In his prominent work *Restraint: A New Foundation for U.S. Grand Strategy*, Barry Posen summarizes a widespread view among traditional security studies scholars, noting that there "might be an argument that such problems [like climate change] strongly affect the sovereignty, territorial integrity, power position, and safety of the United States ... [but] this needs to be demonstrated, not assumed."[124] In this paper, we have taken up Posen's suggestion and have investigated whether climate change might affect military power in the underwater realm. In this way, we have tried to connect the non-traditional and the traditional arms of the field of security studies.

To investigate the effect of climate change on anti-submarine warfare, we have used oceanic acoustic simulations to estimate the changes in transmission loss experienced by low-frequency and mid-frequency sound in three deep-water areas of the North Atlantic and the northern Western Pacific, respectively. We found that the acoustic detection of enemy submarines might become much more difficult in the mid-latitude North Atlantic, and moderately more difficult in the mid-latitude Western Pacific — two key areas of geopolitical competition.[125] Our results indicate that the anti-submarine warfare capabilities of the U.S. Navy could be significantly degraded by climate change. For the subtropical Atlantic and for the tropical Pacific, on the other hand, our results suggest that limited change is to be expected.

Countries should investigate more deeply how anti-submarine warfare is likely to evolve, considering the effects of climate change.

Our results do not mean that detecting submarines will be necessarily more difficult in any specific operational context, nor does our analysis predict transmission loss for any specific condition. The detection of submarines at any given time depends on the environmental and operational conditions, which are distinctive to the geographic area, the season, the weather condition, the time of the day, the type of submarine, and the way it is operated, among other things. Our results show that, when using 30-year averages, we can observe relevant differences between the past and the future in terms of transmission loss, with a general trend toward an increase in transmission loss in several of the cases examined. There is reason to believe this trend is already taking place in some areas and that it could accelerate with time. Whether the detection of submarines will become easier or harder in the future will depend on improvements in detection technology, quieting technologies, climate change, and other factors, such as ambient noise. Future research should investigate such factors in more detail.[126]

We have identified a change in underwater conditions that navies could encounter in the future. States could choose to react to this change in different ways, for instance by reorienting some investments toward new detection technologies that do not depend on acoustic propagation. Further research should assess more in detail how sonar performance might change in specific areas, in different seasons, and under specific conditions. Moreover, future research should also explore systematically the effects of climate change on other anti-submarine sensors and systems, in order to more

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[123] Buhaug, "Climate Change and Conflict," 335.

[124] Barry Posen, *Restraint: A New Foundation for U.S. Grand Strategy* (Ithaca, NY: Cornell University Press, 2014), 2.

[125] Posen, "Command of the Commons," 11.

[126] For an excellent introduction to this type of analysis, see for example, Wu Riqiang, "Survivability of China's Sea-Based Nuclear Forces," *Science & Global Security* 19, no. 2, (2011): 91-120, https://scienceandglobalsecurity.org/archive/2011/05/survivability_of_chinas_sea-ba.html; and Cameron L. Tracy and David Wright, "Modelling the Performance of Hypersonic Boost-Glide Missiles," *Science & Global Security* 28, no. 3 (2020): 135-170, https://scienceandglobalsecurity.org/archive/2020/12/modelling_the_performance.html.

accurately identify areas of research that require more attention and the specific technologies that require more investment. In this regard, our findings should be considered as the first step of a much larger research agenda. With these caveats in mind, if confirmed by further research, our results have several important implications for international security and stability.

First, our analysis points to the need for some corrections in the debate about the future of submarine warfare, specifically about ocean transparency. To start, when it comes to acoustic detection, our results suggest that, in some areas and under some conditions, ocean transparency does not seem inevitable. An increase in transmission loss entails a reduction in the range of sound propagation, which will require a greater number of underwater sensors — whether crewed, autonomous, or fixed — to provide persistent coverage of a given area.[127] As a result, monitoring large swaths of seas, and even some choke points, might become more demanding, difficult, and expensive. Moreover, as we noted, the environmental conditions of the oceans vary on an hourly, daily, weekly, monthly, and yearly basis. Such variations can influence the effectiveness of modern sensors, possibly in significant ways. In practical terms, this means that transparency and opaqueness should not be interpreted as binary outcomes, but as two extremes on a spectrum of possible outcomes that are continually shifting. Even if a trend toward ocean transparency were to be confirmed, it should be understood more as an increasing constraint that submarine operations will be subject to, rather than as the end of submarines as a weapon system that can effectively hide from an enemy's sensors to carry out their missions. Submarines would need to adjust their patterns of operations to limit their vulnerability. Whether such constraints would be more pronounced for attack submarines or ballistic-missile submarines is open to debate. On the one hand, attack submarines need to actively maneuver, often at a shallow depth, to prepare and carry out their missions, making them easier to detect. On the other hand, ballistic-missile submarines operate deeper to avoid detection. Future research could investigate the implications of our findings for attack submarines and ballistic missile-submarines more in detail.

Second, an increase in transmission loss, and hence a shorter range of sonar detection, could also have significant consequences for great-power competition, and particularly the U.S.-Chinese competition. A well-known assumption in this rivalry has been America's superiority underwater, specifically regarding submarines and sensors.[128] With time, however, things could change. There is reason to believe, for instance, that China could lower the noise emission of its submarine fleet.[129] Coupled with increased transmission loss, China's progress in quieting technology could erode America's underwater advantage. Moreover, our results suggest that climate change will have a greater effect on underwater sound propagation in the North Atlantic than in the Western Pacific. Such a difference creates an incentive for China (and Russia) to increase submarine operations in the North Atlantic, drawing NATO countries' attention away from the Indo-Pacific while limiting the resources they can redeploy there and forcing the United States to reallocate precious assets and resources to the North Atlantic.

Third, our investigation has potential implications for North Korea and its sea-based nuclear deterrent project. According to our simulations, the range of acoustic propagation is expected to increase for low frequency sounds in the Sea of Japan for submarines operating within a depth of 100 meters. This is of critical relevance for North Korea, which is refurbishing vessels from the 1980s. When put into service, these vessels may be loud and have limited maximum depth. Because of the trends in underwater sound propagation that we have uncovered, the ability of North Korean ballistic-missile submarines to hide from enemy sensors might be further reduced, unless North Korea addresses the existing shortcomings of its vessels — which would require a significant effort.

Fourth, our results speak to a critical aspect of defense politics: weapons acquisition. The procurement, development, and commissioning of new weapon systems is a very long process which, in the case of submarines, takes multiple decades. Because our simulations are for the last decades of this century, they can contribute to the policy and public debate about the future of submarines. In some countries, such debate has led to public calls for halting the procurement of new submarines. Although the naval and submarine community has not taken these calls seriously, such views can have real effects on public opinion, and hence on

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[127] National Research Council, *Distributed Remote Sensing for Naval Undersea Warfare: Abbreviated Version* (Washington, DC: The National Academies Press, 2007), https://doi.org/10.17226/11927; Owen R. Coté, Jr., "Assessing the Undersea Balance Between the U.S. and China," in *Competitive Strategies for the 21st Century: Theory, History and Practice*, ed. Thomas G. Mahnken (Palo Alto, CA: Stanford University Press, 2012), 184-205; Bryan Clark et al., *Sustaining the Undersea Advantage: Transforming Anti-Submarine Warfare Using Autonomous Systems* (Washington, DC: Hudson Institute, 2020).

[128] Riqiang, "Survivability of China's Sea-Based Nuclear Forces," 91-120; Coté, Jr., "Assessing the Undersea Balance Between the U.S. and China;" Zhao, *Tides of Change*; and Wu Riqiang, "Living with Uncertainty: Modeling China's Nuclear Survivability," *International Security* 44, no. 4 (Spring 2020): 84–118, https://doi.org/10.1162/isec_a_00376.

[129] Christopher P. Carlson and Howard Wang, "China Maritime Report No. 30: A Brief Technical History of PLAN Nuclear Submarines," *CMSI China Maritime Reports* 30 (2023), https://digital-commons.usnwc.edu/cmsi-maritime-reports/30.

policy choices. Our results warn caution when it comes to making drastic decisions about weapons acquisition. As our simulations show, ocean transparency is not a given. Countries should investigate more deeply how anti-submarine warfare is likely to evolve, considering the effects of climate change. Specifically, our results for the mid-latitude North Atlantic are of particular interest for countries such as France and the United Kingdom, whose national nuclear deterrent depends, in part, on ballistic-missile submarines. In these countries, the modernization of their submarine fleets has generated lively debates, in part fueled by concerns about ocean transparency. Our findings put these concerns in perspective and suggest that calls for cancelling new classes of submarines should be weighed carefully, especially considering the high exit costs for the submarine industry.

Finally, our results are an important reminder that ocean transparency and opaqueness should not be interpreted as two discrete outcomes. Rather, they are part of a broad spectrum of possible outcomes that could lead to a range of opportunities as well as constraints. Accordingly, trends in underwater warfare should be considered in parallel with trends in surface warfare. The prevailing wisdom suggests that the increasing capabilities of surveillance and strike assets are making surface fleets far more vulnerable, and more vulnerable at greater distances.[130] From this perspective, even if the detectability of submarines were to increase, it would be less of a problem than some ocean transparency proponents claim, given that other military elements of maritime competition, surface platforms, are becoming more vulnerable much faster. Our contribution suggests that climate change will make submarines an even more important naval asset in the future.

Andrea Gilli *is a lecturer at the University of St. Andrews (United Kingdom) and an advisor of the Italian Ministry of Defense.*

Mauro Gilli *is a senior researcher at the Center for Security Studies of the Swiss Federal Institute of Technology in Zurich (ETH-Zurich, Switzerland).*

Antonio Ricchi *is a researcher at the Department of Physical and Chemical Sciences of the University of L'Aquila (Italy).*

Aniello Russo *is senior scientist at the Centre for Maritime Research and Experimentation of NATO Science and Technology Organization in La Spezia (Italy), on special leave from the Department of Science of Life and Environment of the Marche Polytechnic University (Ancona, Italy).*

Sandro Carniel *is head of the Research Division of the Centre for Maritime Research and Experimentation of NATO Science and Technology Organization in La Spezia (Italy).*

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Appendix: *For additional bibliographic and explanatory material for this article, see the online appendix, available at https://css.ethz.ch/content/dam/ethz/special-interest/gess/cis/center-for-securities-studies/pdfs/Appendix_Climate_Change_Military_Power.pdf.*

Image: *U.S. Navy*[131]

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[130] Bryan Clark and Timothy A. Walton, *Taking Back the Seas: Transforming the U.S. Surface Fleet for Decision-Centric Warfare* (Washington, DC: Center for Budget and Strategic Assessments, 2019), https://csbaonline.org/research/publications/taking-back-the-seas-transforming-the-u.s-surface-fleet-for-decision-centric-warfare/publication/1.

[131] For the image, see https://www.dvidshub.net/image/591905/submarine-conducts-alpha-trials-atlantic-ocean#.T8j4AL8Z9hE#ixzz1wYwz2rGG.