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

This is the online appendix for the article Andrea Gilli, Mauro Gilli, Antonio Ricchi, Aniello Russo, and Sandro Carniel, "Climate Change and Military Power: Hunting for Submarines in the Warming Ocean," *Texas National Security Review* (forthcoming). This appendix contains additional bibliographic and explanatory material for the article that, for space reasons, we could not include in the printed version. This appendix is organized numerically, with each number corresponding to the footnote in the printed article.

Footnote 4: The relevance of submarines in military operations as well as for conventional and nuclear deterrence is often underappreciated by the public (as well as by some academics). According to some, this outcome stems from the fact that the "silent service" (how the U.S. submarine force is nicknamed) is often "too silent." See for example the statement by former Representative of Connecticut Representative of Connecticut Rob Simmons in *U.S. Navy's Future Submarine Force Structure: Hearing Before the Projection Forces Subcommittee of the Committee on Armed Services, House of Representative 109th Congress, Second Session* (Washington, DC: U.S. Government Printing Office, 2006), 3.

Footnote 6: See also Paul Ingram, "Trident: The Need for a Comprehensive Risk Assessment," *Short policy brief* (BASIC, 23 November 2015); Paul Ingram, "Will Trident Still Work in the Future?" *Short policy brief* (BASIC, 22 January 2016), 8-17; David Hambling, "The Inescapable Net: Unmanned Systems in Anti-Submarine Warfare," *Parliamentary Briefings on Trident Renewal Briefing No.1* (BASIC, JULY 13, 2016); James Holmes, "Sea Changes: The Future of Nuclear Deterrence," *Bulletin of the Atomic Scientists*, Vol. 72, No. 4 (July 2016), 228–233; Bryan Clark, "Undersea Cables and the Future of Submarine Competition," *Bulletin of the Atomic Scientists*, Vol. 72, No. 4 (July 2016), 234–237; Elizabeth Mendenhall, "Fluid Foundations: Ocean Transparency, Submarine Opacity, and Strategic Nuclear Stability," *Journal of Military and Strategic Studies* Vol. 19, No. 1 (October 2018), 119-158; Zachary Kallenborn, "If the Oceans Become Transparent," Proceedings Vol. 145, No. 10 (October 2019); Roger Bradbury, Scott Bainbridge, Katherine Daniell, Anne-Marie Grisogono, Ehsan Nabavi, Andrew Stuchbery, Thomas Vacca, Scott Vella, Elizabeth Williams, *Transparent Oceans? The Coming SSBN Counter-Detection Task May Be Insuperable* (Acton, Australia: National Security College, The Australian National University, 2020); and Natasha Bajema, "Will AI Steal Submarines' Stealth? Better detection will make the oceans transparent—and perhaps doom mutually assured destruction, *IEEE Spectrum* (16 JUL 2022).

Footnote 45: Attenuation is a function of several factors, first and foremost of the frequency of the electro-magnetic wave with the visible light in the blue spectrum being the frequency that has the least attenuation – which is why underwater, objects have a blue tone. The relation between frequency and water attenuation is non-linear. The same applies to acoustic waves, with the lowest frequencies (1-100 Hertz, Hz) being able to propagate for thousands of km (whales communicate across the ocean using such low acoustic frequencies) and the highest frequencies (over 10,000 Hz) being limited to few km or less.

Footnote 46: SOSUS was deployed in the Atlantic (and subsequently in the Pacific). One of the key points where the fixed arrays were deployed is the so-called "GIUK" gap, which stands for Greenland-Iceland-United Kingdom, and refers to the choke points that Soviet submarines had to cross in order to pose a threat for the United States and the North Atlantic supply lines to Europe.

Footnote 49: In addition to *fixed* hydrophones arrays (SOSUS) the U.S. employs since the 1950s, it relies also on *movable* hydrophones arrays (SURTASS and RSSD) mounted on specifically designated surface ships (T-AGOS class) as well as on submarines; on very low, medium and high frequency active sonar and passive sonar on both surface ships and submarines (T-AGOS, "hunter-killer" submarines). It relies also on radar, infrared and laser mounted on both surface ships, aircraft and satellites; and disposable sonar buoys carried and dropped by rotary and fixed wing aircraft (P-3 Orion and P-8 Poseidon) that are intended to capture sound generated by enemy submarines as well as sound reflected by their outer hull.

Footnote 60: The operational implications of false positives go beyond the scope of this paper, but they are of critical importance. False positive problems are very serious, because of the extraordinarily difficult task of getting a weapon on a submarine that has been detected, identified and geolocated. It is not possible to waste prosecution assets like attack submarines or patrol aircraft moving hundreds of miles to investigate a false contact, much less wasting a precious, expensive torpedo on it. In this regard, it is important to add the importance of decoys, which are only going to get better because of technological improvements.

Footnote 66: 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 allows to suppress the noise coming from all of the directions except the one being scanned, thus increasing the signal to noise ratio. Some works call it Directivity Index. The direction of acoustic sound is important because ambient noise is generally isotropic (equal from all directions), whereas the signal of a submarine is anisotropic (it varies with directions, since it originates from a specific direction).

Footnote 67: The sonar equation for an active system (monostatic for simplicity) becomes: $SL - 2TL + TS - NL + AG + PG \geq DT$; where TS is the Target Strength (analogous to radar cross section, it varies according to the specific submarine) and TL is double than the passive system because the acoustic pulse travels from the sonar source to the targeted submarines and back to the sonar receiver. Here SL is defined according by the specific sonar system in use, while for a passive system SL varies according to the sound emitted by the targeted submarine. In case of multistatic sonar, the acoustic receivers can be located at several different locations than the source; consequently, the total TL will be the sum of the acoustic loss travelling from the sonar source to the target and of the acoustic loss travelling from the target to the specific receiver.

Footnote 70: The ideal hull shape avoids protuberances and discontinuities, as they generate turbulence and hence flow noise. The ideal propeller shape is the large multi-blade skew-back propeller, which can rotate at lower speed while generating significant thrust, and which interacts with the waterflow in a way to delay the collapse of voids, thus reducing the risk of cavitation for each speed profile. Newer submarines may be propelled by a pump-jet, rather than by traditional propellers, since pump jets may generate less cavitation. Diesel-electric submarines, especially those whose underwater endurance is enhanced by air-independent propulsion, can cruise underwater for weeks without the need to resurface, while benefiting from the fact that electric batteries, in comparison to diesel engines and even more to nuclear reactors, generate significantly less machinery noise. On propeller shapes, see for example lecture notes of U.S. Naval Academy's EN400 Principles of Ship Performance, Chapter 10, available at https://www.usna.edu/NAOE/_files/documents/Courses/EN400/02.10%20Chapter%2010.pdf.

Footnote 71: As Stefanick wrote, "When the source level is reduced to a sufficiently low value, the maximum detection range approaches the length scale of the submarine itself, and the very idea of acoustic detection loses its meaning. The practical lower limit of submarine noise level is

75-85dB. It may be possible to achieve lower radiated sound levels in functional military submarines, but it is not worth the money, since there is no gain in military effectiveness." Stefanick, *Strategic Antisubmarine Warfare and Naval Strategy*, 173. Pioneered by Germany during World War II, anechoic coating has become more widely employed over the past 30 years. However, its application still poses problems as the coating is particularly vulnerable to conditions of operation of a submarine, which lead to the premature detachment from the hull. See for example William Cole, "Navy Subs Still Show Issue with Stealth Coating," *Military News* (March 6, 2017), https://www.military.com/daily-news/2017/03/06/navy-subs-still-show-issue-stealth-coating.html; and H. I. Sutton, "U.S. Navy Submarines May Have Stealth Problems, But They're Not Alone," *Forbes* (Oct 13, 2019), https://www.forbes.com/sites/hisutton/2019/10/13/us-navy-submarines-may-be-easier-to-detect-but-they-are-not-alone/?sh=594cf55f987c.

Footnote 73: The array gain depends mostly on the number of hydrophones used, so larger arrays obtain increased array gain and make detection easier.

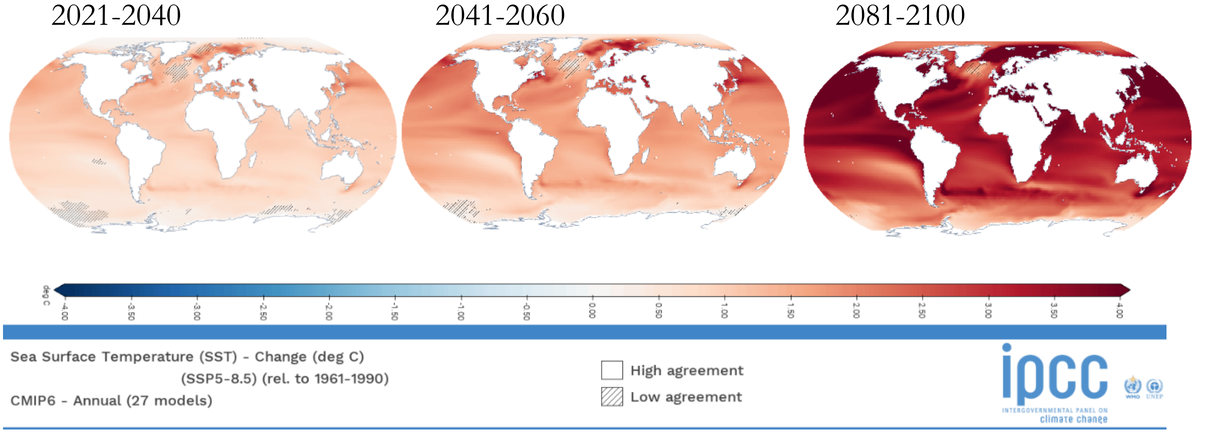
Footnote 80: Salinity has only a minor influence. This can be seen in the simplified equation that illustrates the relation between sound speed (c, in meter per second), temperature (T, in degrees centigrade), salinity (S, in parts per thousand) and depth (z, in meters): $c = 1449.2+4.6T-0.055T^2 +0.00029T^3 + (1.34-0.01T)(S-35) +0.016z$.

Footnote 81: Temperatures of the ocean are generally increasing, while salinity is increasing or decreasing according to different areas and depths. Climate change can modify how temperature and salinity vary in both horizontal and vertical directions (the measure of the variation of a variable in 3-D space is called the gradient), and consequently the gradients of sound speed which determine the pathways followed by the propagating sound.

Footnote 82: Atmospheric and oceanic temperatures, precipitation regimes, and the rate of ice melting will generate a variability in the position of fronts between water masses with different properties as well as changes in frontal and vertical gradients, in turn modifying patterns of sound propagation.

Footnote 87: The following picture shows expected variation in sea surface temperature.

Expected Increase in Sea Surface Temperatures



Adapted from the V. Masson-Delmotte et al. (eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* Cambridge, UK: Cambridge University Press, Cambridge, 2021).

Footnote 96: Outputs are available at https://esgf-node.llnl.gov/search/cmip5/. The presented analysis is aimed at demonstrating the possibility that climate change might significantly affect submarine detection. In order to obtain a robust assessment, a multi-model approach using recent high-resolution climate outputs would be needed.

Footnote 98: There are several underwater acoustic propagation models, such as RAM, SAFARI, KRAKEN, C-SNAP, PROSIM, PAREQ, and SNAP-RD. We used BELLHOP because it is widely adopted in the underwater acoustic community. The use of other acoustic models would not change the results. It is important to note that average transmission loss may not equal the transmission loss from an average profile. However, the latter provides valuable indications of the general trend. Moreover, our simulations have been conducted in deep waters only, so that interactions with seabed are minimized or absent, and thus reduce the differences between average transmission loss and transmission loss from an average profile. Moreover, since we assess the difference between the average transmission loss in two different periods, there is no reason to believe that different models would affect the difference between the means. It is important to note that average transmission loss may not equal the transmission loss from an average profile. However, the latter provides valuable indications of the general trend. Moreover, our simulations have been conducted in deep waters only, so that interactions with seabed are minimized or absent, and thus reduce the differences between average transmission loss and transmission loss from an average profile.

Footnote 99: This layering of the ocean forms the so-called thermocline. In low and mid-latitude oceanic waters, the upper layer of the waters (order 100 m) is warm (order 15-25 °C), followed by a rapid decrease of temperature with depth (the thermocline) and then a slight decrease below order 1000m depth (where the temperature is usually below 4 °C). Because of the combined effect of temperature and depth on the sound speed, a sound speed minimum is generated at some hundreds m depth. This minimum of sound speed creates the so-called SOFAR (or simply deep sound) channel by refraction of the sound propagating in the vertical layer characterized by the presence of the sound speed minimum. Because of the refraction, the acoustic waves propagate trapped in the SOFAR channel. The depth of the sound speed minimum is shallower at low latitude, becomes deeper at mid-latitudes and shoals toward the Arctic region; in the Arctic Ocean, a deep sound speed minimum is almost absent in several regions.

Footnote 100: Vertical sound speed gradients can cause an upward refraction of the sonar pulse, which bounces at the sea surface in the so-called convergence zone without interacting with the (deep) seafloor and continues to propagate, possibly reaching a second convergence zone. When convergence zones form, the area investigated by an active sonar can have a large radius (several tens of km), but with wide shadow zones in it; the submarine can be detectable for just a few minutes while it is crossing the convergence zones.

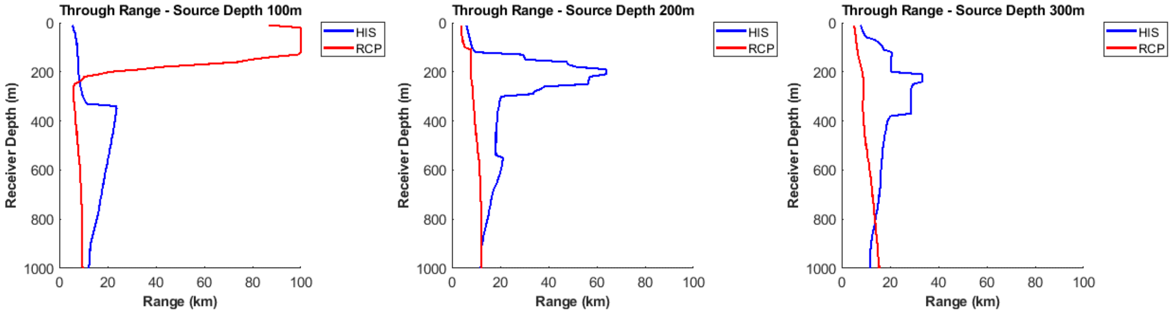
Footnote 101: Fronts are borders between adjacent water masses (i.e., marine areas) that have sharp contrasts in temperature and salinity. When sound waves cross a front, their propagation pattern changes because of the sudden variation of the thermohaline properties, that generates a sudden variation of the sound speed. Moreover, fronts scatter sound into a variety of vertical angles, leading to transmission loss which reduces the range of propagation. The exact distribution is determined by the acoustic frequency and the specific parameters of the front. Internal waves are oscillations of the layered water column that can reach several tenths meters in height and several kilometers in horizontal extension, with periods ranging from several minutes to several hours, comparable to the familiar ocean surface waves, albeit within the water column. Internal waves affect sound propagation in both space and time, because they cause sound speed field's oscillations that modify acoustic propagation depending on the local characteristics of the internal waves. The limited density contrast existing between two layers in the water column allows for internal waves reaching higher maximum heights than surface waves. Rain produces noise. Waves scatter the propagating sound. Wind and breaking waves produce air bubbles (that scatter the sound) and noise.

Footnote 104: Quiet patrol speed is about 5–12 knots. For publicly available data about Soviet/Russian and Chinese submarines, see for example Stefanick, *Strategic Antisubmarine Warfare,* 272-283; E.V. Miasnikov, *The Future of Russia's Strategic Nuclear Forces: Discussions and Arguments* (Moscow, Russia: Center For Arms Control, Energy And Environmental Studies , Moscow Institute of Physics and Technology 1995), Appendix 2 - Estimates of Submarine Detection Ranges; and Andrew S. Erickson, Gabriel B. Collins, Lyle J. Goldstein, and William S. Murray, "Chinese Evaluations of the U.S. Navy Submarine Force," *Naval War College Review* Vol. 61, No. 1 (Winter 2008), 68-86; *The People's Liberation Army Navy: A Modern Navy with Chinese Characteristics* (Washington, D.C.: U.S. Office of Naval Intelligence, August 2009, 22; Hans M. Kristensen, "China's Noisy Nuclear Submarines," *Federation of American Scientists* (21 November 2009), https://fas.org; Jeffrey Lewis, "China's Noisy New Boomer," *Arms Control Wonk* (24 November 2009). About Soviet quieting advances in the 1980s, see Wende A. Wrubel "The Toshiba-Kongsberg Incident: Shortcomings Of COCOM, and Recommendations For Increased Effectiveness Of Export Controls To The East Bloc," *American University Journal of International Law and Policy* Vol. 4, N. 24 (1989), 241–273; Robert W. Hunter with Lynn Dean Hunter, Spy Hunter: Inside the FBI Investigation of the Walker Espionage Case (Annapolis, Md.: Naval Institute Press, 1999), 203.

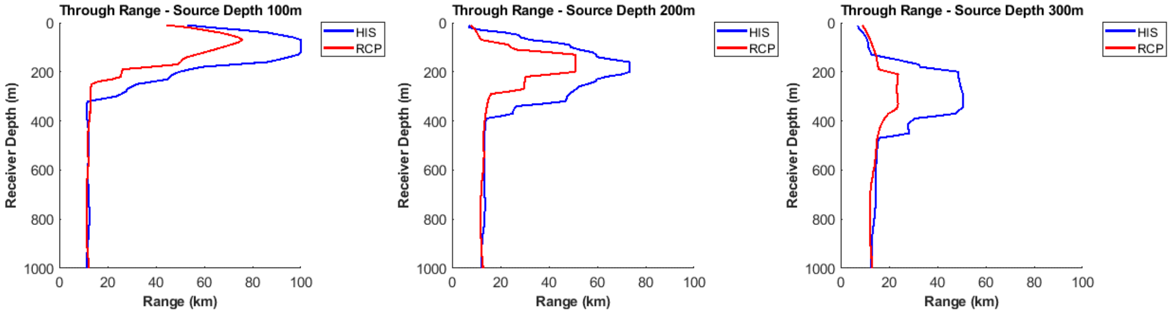
Footnote 107: The FOM can be obtained by re-arranging the sonar equation by defining the signal-to-noise ratio to describe the transmission loss such that the signal-to-noise ratio equals the detection threshold. For passive sonar, the equation is SL - TL = NL – AG + DT where SL is the Source Level, TL the Transmission Loss, NL the Noise Level, AG the Array Gain, for simplicity here including the Processing Gain, DT the Detection Threshold, and FOM = SL + AG – (NL + DT). All values are expressed in dB.

Footnote 110: We report explicative graphs that are accessible to non-experts. The obtained figures with the full range of depths, when examined by a non-trained eye, result very difficult to interpret, consequently we chose to show representative graphs easy to interpret. We have modified the scales of the graphs so as to show range of detection changes, also when the magnitude of this change is very limited. Here we report the results of the Figure of Merit for active sonar.

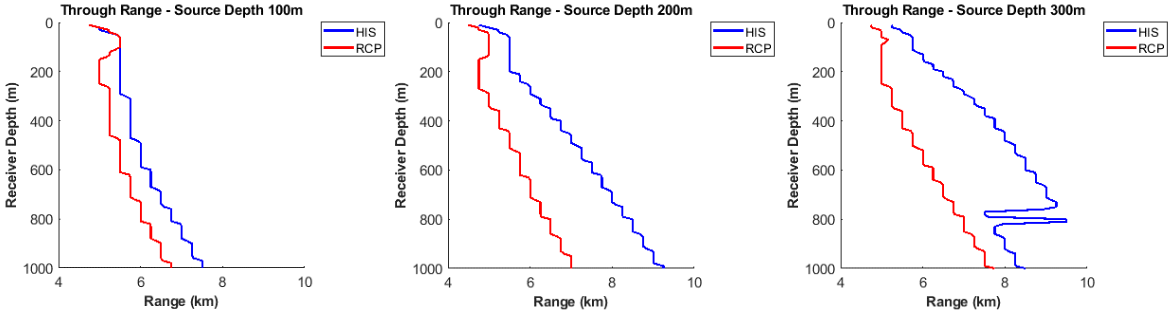
Detection Range with FOM=80dB (January, 100Hz) His: 1970-99, RCP: 2070-99
Outside the Bay of Biscay (range: 0-100km)



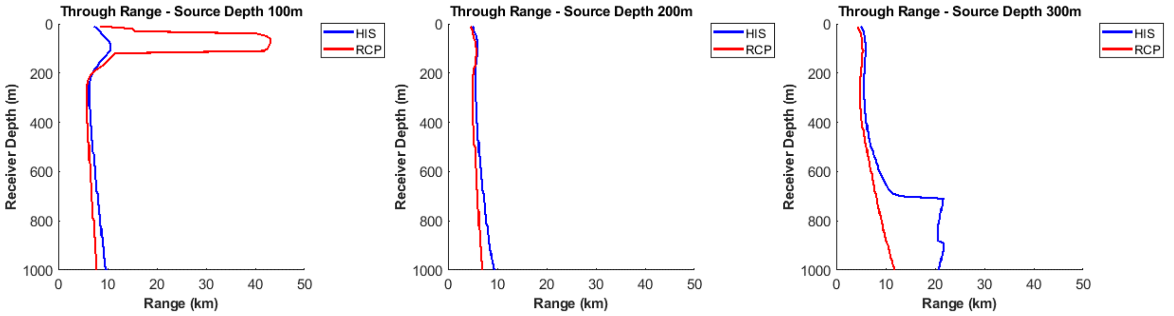
Greenland Sea (range: 0-100km)



Philippine Sea (range: 0-10km)



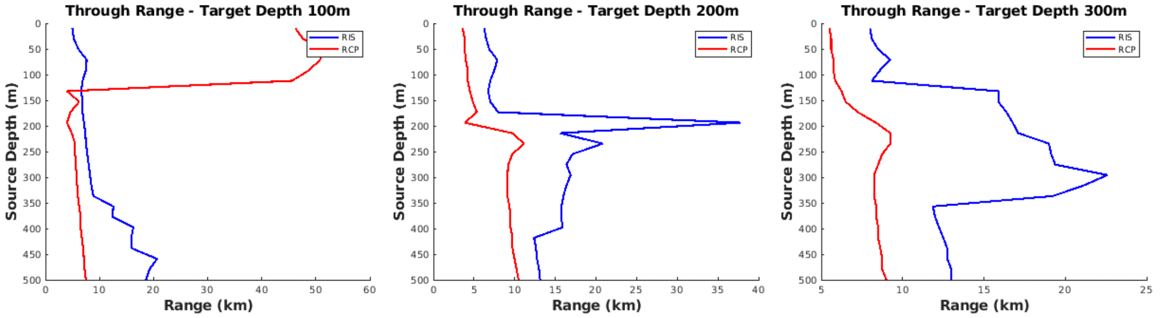
Sea of Japan (range: 0-50km)

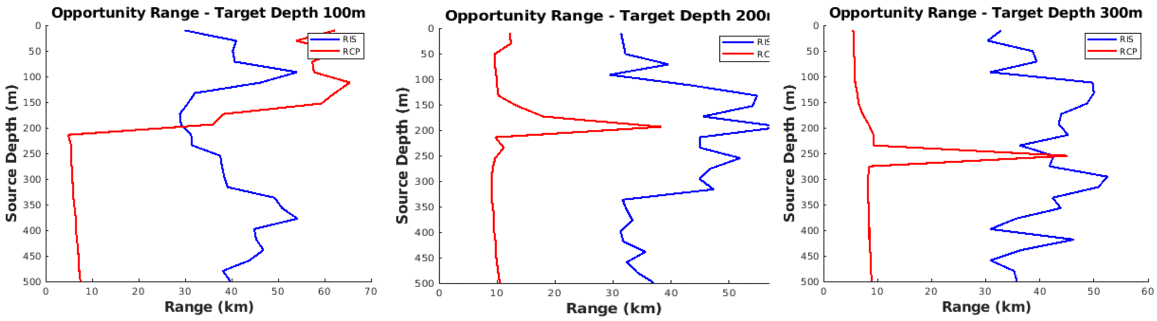


Footnote 116: Here we report the results of the Figure of Merit for active sonar.

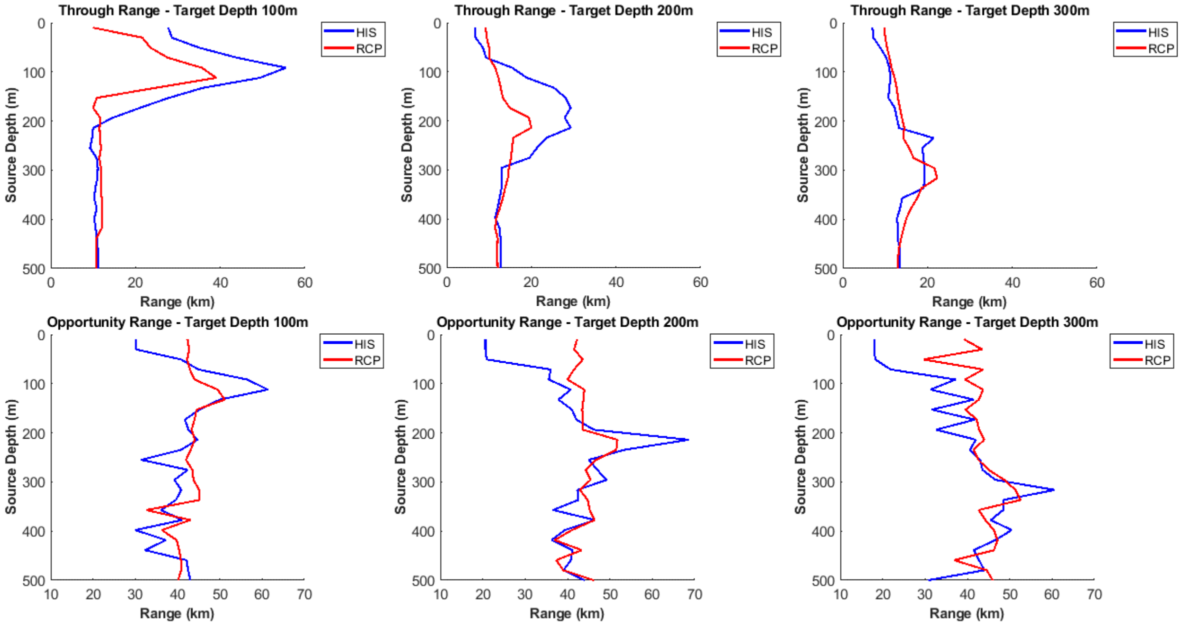
Detection Range with FOM=160dB (Jan, 2000Hz) RIS: 1970-99 RCP: 2070-99

Outside the Bay of Biscay (range: 0-40km)

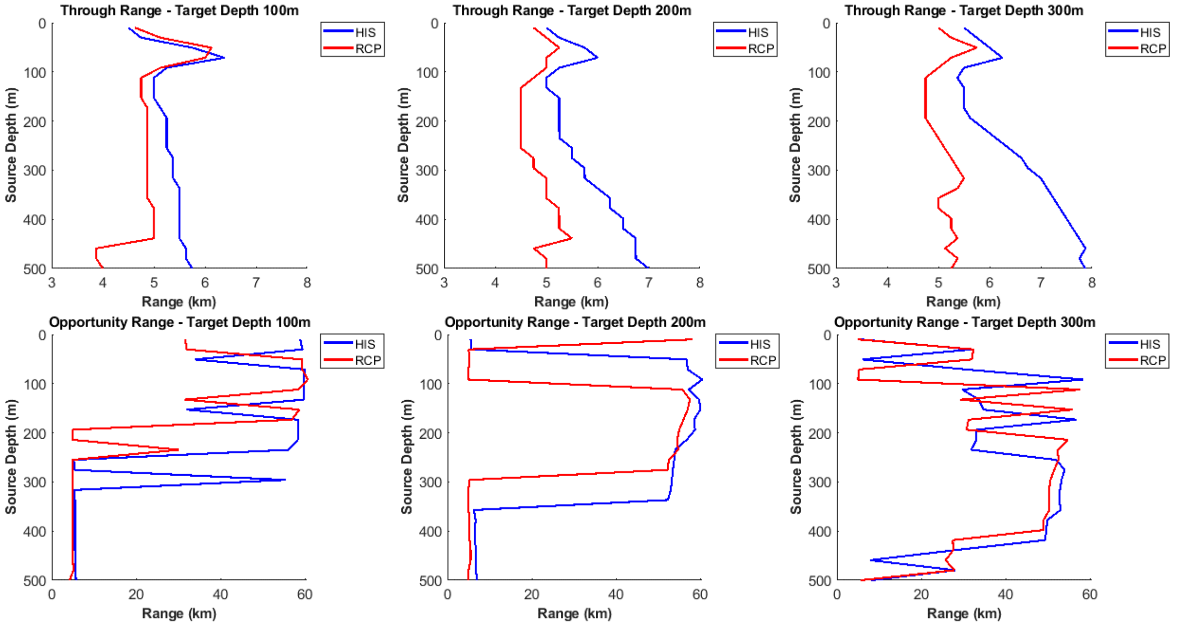




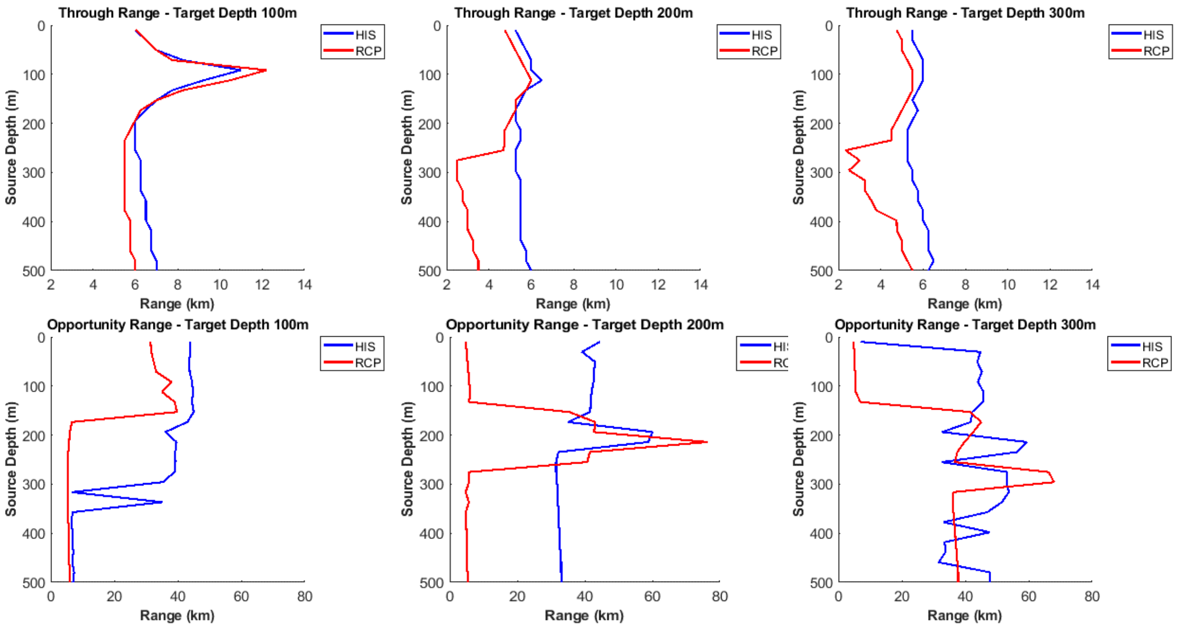
Greenland Sea (range: 0-60km)



Philippine Sea (range: 0-8km)



Sea of Japan (range: 0-14km)



Footnote 127: For example, because of the reduction in the range of sound propagation, Deployable, Autonomous, Distributed, Sensor (DADS) would be able to detect a submarine only when it happens to be exactly at the range of the convergence zone. This requires either that the submarine cruise at a sufficiently close range to these sensors (for fixed ones), or that these sensors move sufficiently close to the submarine (for moving ones). Along the same lines, increases in transmission loss for active sonar will also affect the performance of sensors such as multi-static active coherent (MAC) source sonobuoys that have a fairly good range of detection. As the range of detection shrinks, the number of such sensors will have to increase in order to cover a given area. Other systems, such as fixed distributed systems (FDS) that are attached to the ocean floor and can listen to sound radiated downward (Reliable Acoustic Path, or RAP) are very effective in detecting even the quietest submarines, but have an extremely short range and hence can be used only in choke-points (such as the between Greenland, Iceland and United Kingdom, or GIUK gap or between the islands of the first island chain in the Western Pacific). For a discussion of all these different systems,