The future evolution of mid-frequency active sonar performance in a changing ocean

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Abstract: *Climate change and global political-economic developments affect the future performance of underwater acoustic instruments through several interrelated channels: changes in sound velocity profile and volume attenuation in a physically evolving ocean, combined with a likely increase in ambient noise from shipping traffic and route changes. This multifactorial problem has already been the subject of several published analyses, with controversial conclusions. Climate change is primarily driven by changing atmospheric CO2 concentration; for this parameter, we have adopted the IPCC's Shared Socio-Economic Trajectory SSP5-8.5, which is the most pessimistic, but apparently the most probable curve. The variations of physical ocean parameters over the 21st century have been the subject of numerous models, the results of which are available online: 120 models were compared in the Coupled Model Intercomparison Project - Phase 6 (CMIP6). We have chosen the predictions of the ocean climate model CNRM-ESM2, developed by the CNRM (Toulouse, France), which not only has a good reputation, but also lies in the middle of the very different trends proposed by the 120 models. In this article, we present preliminary global conclusions based on a planetary-scale analysis of the evolution of the various terms of the Sonar Equation, along with the tactical behavior of sonar use. We restrict ourselves to a generic fictitious active VDS (Variable Depth Sonar) sonar operating in the mid-frequency range (at 2kHz). Global 2°latitude x2° longitude maps of maximum detection ranges are presented. Apart from some local variations, surprisingly simple trends emerge for the period 2019-2100: in both the northern and southern hemispheres, detection ranges remain stable in winter and tend to increase with time in summer, as a result of the contradictory interplay between changes in the shape of velocity profiles (accentuation of permanent and seasonal thermoclines) and reduction in volume absorption.*

Keywords: *climate change, active sonar, variable depth sonar, mid-frequency sonar, sonar performance, sonar equation, performance prediction*

1. SENSITIVITY OF THE SONAR EQUATION TERMS TO ENVIRONMENTAL CONFIGURATION

One traditional way to quantify the performance of an active sonar system is to evaluate the signal excess (SE), which is the difference between the signal-to-noise ratio (SNR) at the end of the full processing sequence and a detection threshold (DT). This is the well-known active sonar equation:

$$SE = SL–2TL + TS - ((NL–AG)(+)RL) + PG - DT \tag{1}$$

The detection threshold (DT) is an arbitrarily parameter tuned by the sonar operator according to his or her tolerance of false alarms. Source level (SL), self noise, array gain (AG) and time processing gain (PG) are essentially dependent on the sonar technology and cinematics, whereas the target strength (TS) is a characteristic of the target. The remaining terms—transmission loss (TL), ambient noise level, and reverberated level (RL)—are characteristic features of the environment and geometrical configuration (i.e., source and sonar locations and orientation). The propagation conditions may affect the directionality of ambient noise and, consequently, the array gain.

Figure 1 displays a flowchart summarizing the causal relationships between long-term, variable environmental features (on the left) and the associated acoustic properties of the ocean (in the center). These properties, in turn, are connected to the terms of the sonar equation, which they influence (on the right). The sound channel directly impacts the propagation of sonar pings, ambient noise, and reverberation. In other words, it influences TL, NL, and RL. The sound channel also affects the directionality of ambient noise and plays a role in array gain. Furthermore, the shape of the sound speed profile is of primary importance in optimizing the performance of variable depth sonars (VDS) for target detection. The target adopts a depth that minimizes its detectability. Thus, the shape of the sound channel directly influences sonar operating tactics and target depth. The sound channel is primarily characterized by the shape of the sound speed profile and volume attenuation. These characteristics depend mainly on ”hydrospheric” parameters, such as the temperature, salinity, and pH of water masses.

Ocean-atmosphere interactions impact TL, NL, RL, and AG by modifying the shape of the sound speed profile through the formation of shallow mixing layers (acoustic surface channels). These interactions are also responsible for ambient noise sources (e.g., wind, wave breaking, and rain) and surface loss due to wind-generated surface waves. The impact of ice cover on propagation, noise, and reverberation, which is limited to polar regions, will be disregarded in this article. Similarly, the impact of traffic noise and its evolution is ignored, which is reasonable apart from the traffic lines themselves, at 2 kHz. The biosphere plays an important role in ambient noise and as a source of reverberation. Human behavior is a major contributor to changes in sonar performance. Humans appear to be the main source of low-frequency noise, particularly close to shipping lanes and fishing zones, which are sensitive to historical and economic changes. We will firstly ignore the technological advance, even if there should be no stop in the increase of active sonar efficiency through new transmitted frequencies and waveforms, improvements to array technology, and advances in time processing. At the same time, more efficient anechoic coatings will likely improve target discretion against active sonar. All ”technological” terms in the sonar equation are affected, including the detection threshold, which could be lowered by improved echo-false alarm discrimination made possible by AI.

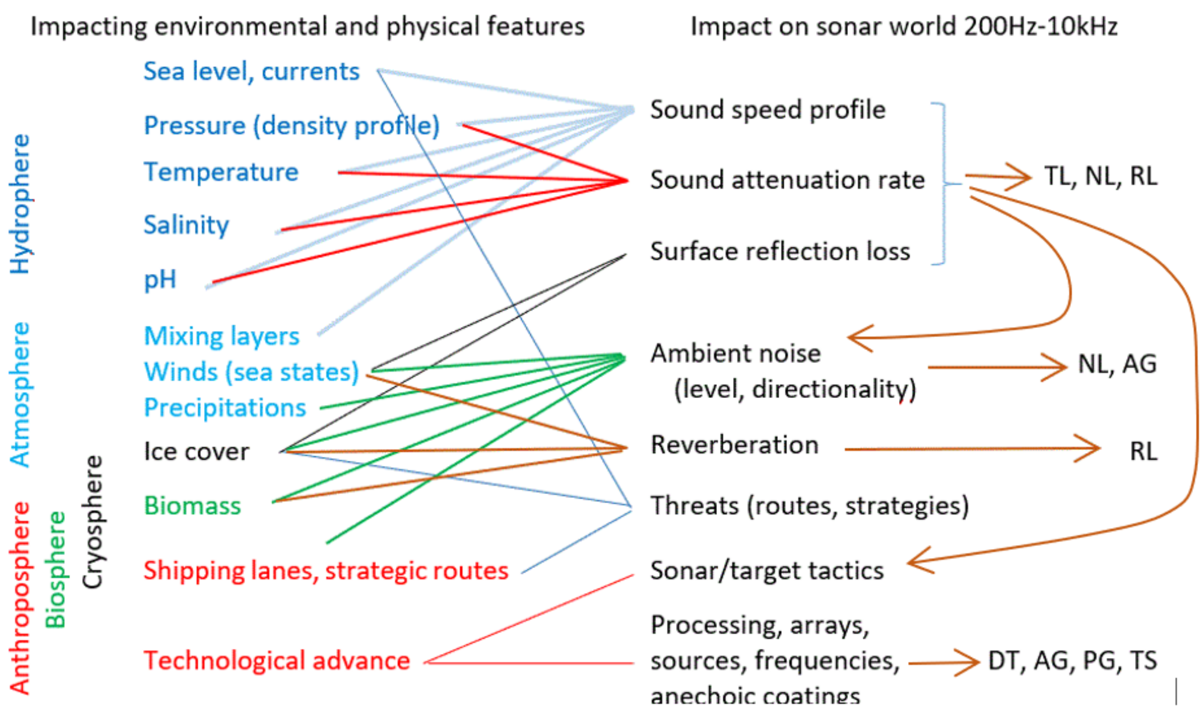

Figure 1: Connections between physical, environmental and acoustical features of the ocean and the various terms of the Sonar Equation.

2. METHODOLOGY FOR PREDICTING THE FUTURE EVOLUTION OF SONAR EQUATION TERMS

All natural and human-origin features impacting the sonar equation terms, which are listed in the previous section, have undergone significant observed modifications in the past and will likely continue to do so in the future. For example, considering the properties of water, the observed past surface temperature has increased at a rate of 0.1°C per decade over the last 50 years, and the pH has decreased by 0.025 per decade, reducing its basicity (”acidification”). The biomass was strongly reduced (factor 1/2 for predator fishes at trophic level 2-3). The shipping almost never stopped increasing since the end of World War II, resulting in an increase of more than 3 dB per decade of low frequency ambient noise. The future trajectory of sonar performance is contingent upon the future trends of these phenomena and others.

Regarding the physical features of the ocean and atmosphere, climate change is the main cause of change. It is primarily driven by the future trajectory of atmospheric CO2 concentration. For this parameter, we adopted the IPCC’s Shared Socioeconomic Pathway (SSP) 5-8.5, the most pessimistic and apparently most probable curve. The variations of physical ocean parameters over the 21st century have been the subject of numerous models, the results of which are available online: 120 models were compared in the Coupled Model Intercomparison Project - Phase 6 (CMIP6). We chose the predictions of the CNRM-ESM2 ocean climate model, developed by the CNRM in Toulouse, France. This model has a good reputation and provides trends that fall between the wide range of trends proposed by the 120 models. This ”median” trend is ideal for our initial investigation. The NOAA website provides the sampled vertical variations of ocean parameters by 2100 according to the CNRM-ESM2 model down to a depth of 500

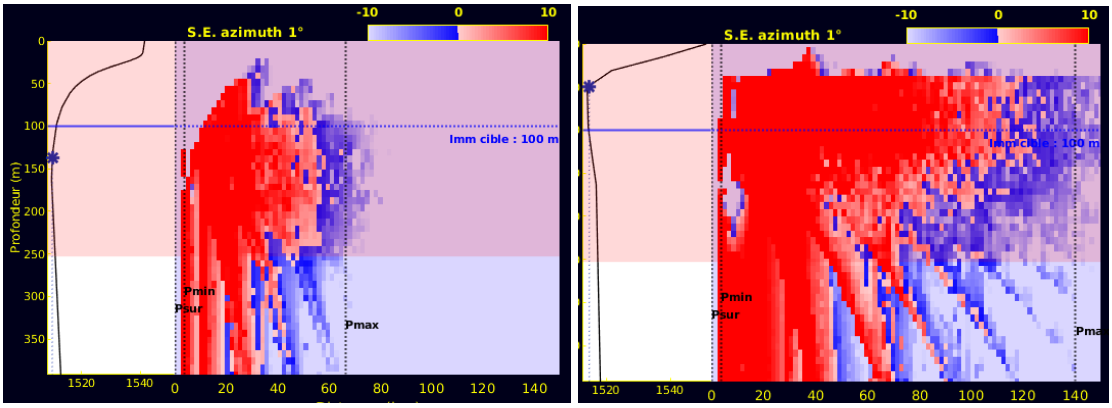

Figure 2: Vertical views of Signal Excess in August for years 2019 (left) and 2100 (right) at a same Mediterranean location (ranges in km); the sonar depth (asterisk) depends on the shape of the sound speed profile.

meters. We extrapolate at greater depths using an exponential decay inspired by past variability.

In this article, we examine the evolution of the performance of one mid-frequency active variable depth sonar over the 21st century. The properties of this VDS are listed below:

Transmitted waveform: Central frequency 2 kHz, Bandwidth 250 Hz, Pulse duration 4 s

Source level: 216 dB (omnidirectional)

Towing ship velocity: 12 knt (impact on self-noise)

Line array’s Directivity Index: 20 dB (broadside)

Target Strength: 10 dB

Local mean seastates of considered seasons (impact on ambient noise and surface loss)

The specific feature of a VDS is its ability to be towed at variable depths and adapt to the local sound-speed profile according to specific rules, maximizing its detection efficiency. Similarly, the target chooses depths that minimize its indiscretion by avoiding surface channels and local sound speed minima. Our evaluations of the Signal Excess take this tactical game into account by changing the VDS depth according to the local sound speed profile for the given season and year. Figure 2 illustrates the radical impact that depth adaptation has on the resulting SE: the future shaping of the surface thermocline will result in a sound speed minimum at a depth that is very different from what it is now. Then, the VDS will not be towed at the same depth.

With the help of the sonar performance tool proprietary Thales software TARANIS, we computed the three-dimensional (3D) distributions of SE along bearing angle, range, and depth for the VDS located at the meshes of a 2° latitude x 2° longitude grid over the world ocean; examples of such results out from our computation are the vertical cuts, at given bearing angle, of the SE displayed by Figure 2.

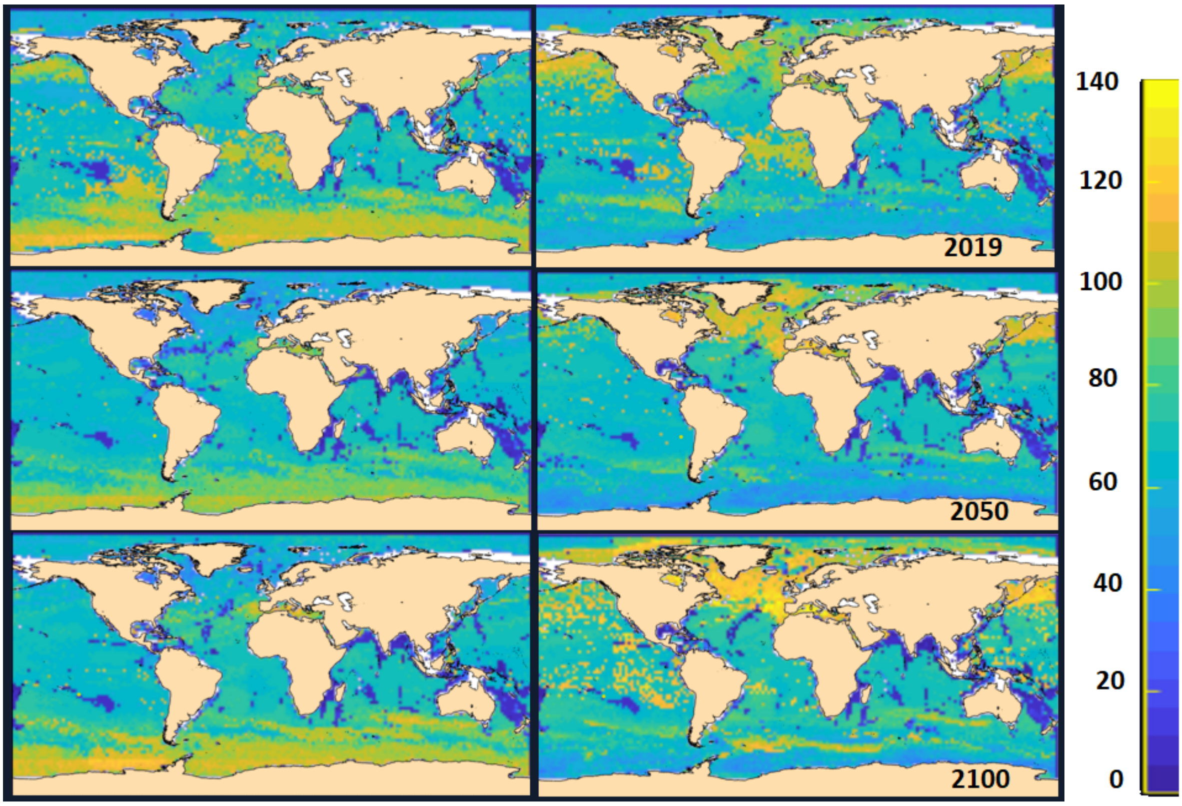

Figure 3: World maps of maximum detection range, in kyd, in February (left column) and August (right column) for years 2019, 2050 and 2100.

3. PRELIMINARY RESULTS

To get a direct sense of the planetary scale, it is necessary to extract and map some scalar moments of the full distributions of SE. Perhaps the most striking characteristic is the maximum detection range, which is evaluated at each sonar location by inspecting all bearing angles and possible target depths. Global 2° latitude x 2° longitude maps of maximum detection ranges are presented by Figure 3. Apart from some local variations, surprisingly simple trends emerge for the period 2019-2100. In the northern hemispheres, and particularly in Northern Atlantic and North-Western Pacific, detection ranges remain stable in winter and tend to increase with time in summer, as a result of the contradictory interplay between changes in the shape of velocity profiles (accentuation of permanent and seasonal thermoclines) and reduction in volume absorption due to water acidification. It seems that detection in the second Convergence Zone will become less uncommon in the future. Similar but less marked trends can be observed in the southern hemisphere. Certain areas of limited extension are currently unfavorable to the use of VDS and are likely to remain so until the end of the century: Arabian Sea, Bay of Bengal, Indo-Pacific and South-Western Pacific.

4. CONCLUSION AND PERSPECTIVES

The multifactorial problem of the impact of future ocean changes on sonar performance has already been the subject of many published analyses, as demonstrated by the extensive bibliography in reference [4]. No global conclusion seems to have emerged, and the results of these analyses may sound controversial. Many studies are limited to specific basins or regions (e.g. references [1], [2] [4]); there is a particular interest in Arctic and northern waters. In many respects, our analysis aligns with reference [3].

Future work should include the following extensions to this very preliminary article:

- Other metrics of sonar performance than just maximum detection range (detection volume, range of 1st contact loss, etc.);
- Additional environmental data (a set of other predictive models of ocean warming than CNRM-ESM2 should be selected);
- Additional modeling of global sonar performance (trying to give some figures in dB to the technological advances, trends towards lower frequencies);
- Additional modeling of threat evolution (trying to include realistic trends in anecoic coating technology);
- Evolution of performances for other sonar types (dipping sonar, hull mounted sonar, passive sonar);
- Evolution of optimal active sonar frequencies [0.1, 10]kHz, by basin and season;
- Impact trends on multistatism, fixed networks and acoustic communications.

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