THE IMPACT OF OCEAN ACIDIFICATION ON UNDERWATER OPERATIONS

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Ocean acidification, driven by increased atmospheric carbon dioxide concentrations, induces significant chemical changes in the marine environment, with direct implications for submarine operations. This paper analyses the impact of decreasing oceanic pH on sound propagation, sonar performance, the strength of materials used in submarine construction, and the reliability of communication systems. It also highlights related operational risks, such as damage to acoustic equipment, reduced detection and identification accuracy, and heightened vulnerabilities in surveillance and navigation missions. These issues underscore the necessity of adapting underwater tactics and technologies to maintain operational efficiency amid constantly changing environmental conditions.

Future research directions are proposed, including advanced modelling of acidified environments, the development of innovative materials, and the optimization of acoustic communication systems. It is essential to develop predictive models that integrate oceanographic and chemical variables to anticipate changes in pH and other relevant parameters, enabling operational strategies to be planned and adjusted in real time. The findings emphasize the importance of continuous monitoring of oceanographic parameters and adopting a proactive approach to ensuring the efficiency and safety of submarine operations within the context of global climate change.

Keywords: ocean acidification; oceanographic parameters; submarine warfare; industrial processes; marine ecosystems;

INTRODUCTION

The process of acidification of ocean waters can no longer be considered a subject of a strictly scientific nature, as it has become an operational reality, with direct implications on maritime activities and naval security strategies. This change in the marine environment significantly impacts equipment, techniques and operations at sea, requiring specific adaptations and measures to address the new challenges posed by the chemical imbalance of the oceans. The naval forces must anticipate the consequences of this phenomenon, adopting a proactive approach in developing and modernizing the submarine capabilities. The integration of chemical data into mission planning and execution is thus becoming a key condition for maintaining strategic submarine superiority over the coming decades.

At the same time, ocean acidification is a major challenge not only for marine biodiversity but also for the deployment of submarine actions. Chemical changes in seawater influence sound propagation and sonar performance, the strength of materials used in submarine construction, and the reliability of communications. These effects will fundamentally transform the technologies used both in the civilian field (exploration, communications, research) and in the military field (submarine navigation, surveillance, submarine combat).

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Ocean acidification refers to the gradual decrease in the pH of seawater over extended periods, a process mainly driven by the absorption of carbon dioxide (CO_2) from the atmosphere. When CO_2 dissolves in ocean water, it triggers chemical reactions that increase hydrogen ion (H^+) concentration, leading to acidification and a reduction in carbonate ions, which are essential for the formation of calcified shells and skeletons of marine organisms (oceanservice.noaa.gov, 2025).

Since the *Industrial Revolution* (circa 1750), the oceans have absorbed between one-third and half of total anthropogenic CO_2

emissions, causing ocean pH to drop from about 8.19 to 8.05 – an increase in acidity of approximately 30% (www.britannica.com). This acidification results from high anthropogenic CO_2 emissions from activities such as transportation, industrial processes, and agriculture.

Atmospheric CO_2 levels have risen from about 280 parts per million (ppm) before industrialization to nearly 400 ppm today, with an accelerated growth rate. Currently, around 50% of anthropogenic CO_2 is found within the upper 400 meters of the ocean, with gradual infiltration into deeper layers. In open ocean regions, deep-water chemical changes will occur centuries later than surface layers.

Although global warming and ocean acidification are distinct phenomena, both stem from increased CO_2 emissions. Present-day atmospheric CO_2 concentrations are the highest in the last 800,000 years – possibly even in the last 20 million years (www.britannica.com).

Without the oceans' absorptive role, atmospheric CO_2 levels would have been much higher, exacerbating global warming effects such as sea level rise, altered climate patterns, and intensified extreme weather. However, this absorptive capacity causes major chemical changes in marine ecosystems.

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DATA AND METHODS

According to available data, global CO_2 emissions from fossil fuels and industry reached 37.01 billion metric tons in 2023 and 37.41 billion metric tons in 2024 (Ib.). Since 1990, global emissions have increased by over 60% *(table 1, figure 1).*

Table 1: Global CO_2 emissions between 1940 and 2024
(www.statista.com)

Year	CO_2 (Billion MT)	Year	CO_2 (Billion MT)
1940	4.84	1983	18.99
1941	4.97	1984	19.64
1942	4.96	1985	20.31
1943	5.04	1986	20.61
1944	5.12	1987	21.25
1945	4.26	1988	22.08
1946	4.65	1989	22.38

Year	CO_2 (Billion MT)	Year	CO_2 (Billion MT)
1947	5.15	1990	22.52
1948	5.42	1991	22.97
1949	5.18	1992	22.31
1950	5.93	1993	22.52
1951	6.38	1994	22.74
1952	6.47	1995	23.27
1953	6.65	1996	23.99
1954	6.79	1997	24.12
1955	7.44	1998	24.02
1956	7.93	1999	24.56
1957	8.19	2000	25.20
1958	8.42	2001	25.39
1959	8.85	2002	25.95
1960	9.39	2003	27.31
1961	9.41	2004	28.25
1962	9.75	2005	29.21
1963	10.27	2006	30.18
1964	10.82	2007	31.06
1965	11.31	2008	31.58
1966	11.86	2009	31.02
1967	12.24	2010	31.81
1968	12.90	2011	33.91
1969	13.76	2012	34.38
1970	14.90	2013	34.72
1971	15.50	2014	34.77
1972	16.22	2015	34.72
1973	17.08	2016	34.73
1974	17.01	2017	35.29
1975	17.05	2018	36.00
1976	17.99	2019	36.37
1977	18.48	2020	34.37
1978	19.06	2021	36.02
1979	19.60	2022	36.50

Year	CO_2 (Billion MT)	Year	CO_2 (Billion MT)
1980	19.48	2023	37.01
1981	19.02	2024	37.41
1982	18.87	-	-

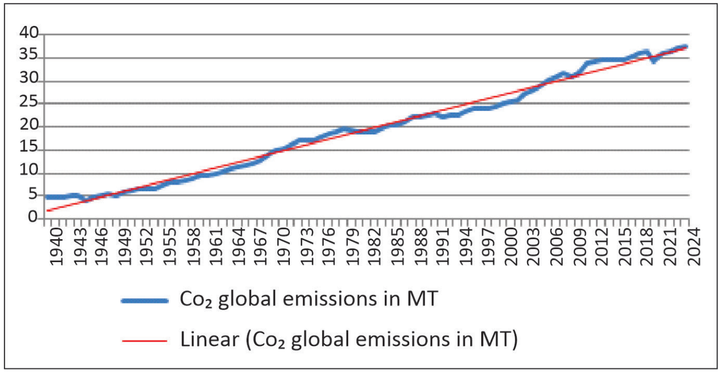

Figure 1: Global CO_2 emissions trend, 1940-2024 (Ib.)

To reconstruct historical ocean chemistry, researchers analyse fossil shells or ice cores from Greenland and Antarctica. These methods indicate that current CO_2 levels and pH decline are unprecedented in the last 800,000 years.

Historical events, such as the Paleocene-Eocene Thermal Maximum (66 to 56 million years ago), when massive CO_2 releases occurred over thousands of years, show that the current rate of acidification is unprecedented in speed (www.britannica.com).

Naturally, seawater has a pH of approximately 8.2; since the Industrial Revolution, it has decreased to around 8.05 *(table 2, figure 2)*, equivalent to a 26% increase in acidity (www.statista.com). Studies of the North Pacific Ocean from 1998–2002 confirm progressive acidification trends (Garcia-Ibanez, 2016).

Ocean acidification intensifies in combination with climate change and other environmental stressors, necessitating consideration of their combined effects (Falkenberg, 2020).

Table 2: Average ocean pH values, 1985-2022
(www.statista.com)

Year	Average ocean pH value
1985	8.11
1990	8.1
1995	8.1
2000	8.09
2005	8.08
2010	8.07
2015	8.06
2020	8.05
2021	8.05
2022	8.05

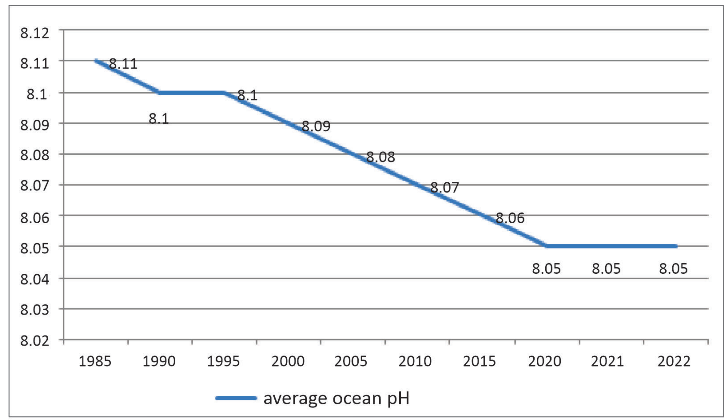

Figure 2: Average ocean pH evolution, 1985-2022 (Ib.)

RESULTS AND DISCUSSION

Ocean acidification directly affects calcifying organisms – corals, molluscs, phytoplankton, and zooplankton-key components of the marine food chain. Primary effects include: corrosion of calcified structures due to lower pH; reduced availability of carbonate ions for shell and skeleton formation; and accelerated acidification, occurring 30-100 times faster than in previous geological epochs.

Intergovernmental Panel on Climate Change/IPCC climate models forecast that atmospheric CO_2 levels may reach 500 ppm by 2050 and 800 ppm by the end of the century, causing a further pH drop of 0.3-0.4 units (IPCC, 2019). In extreme conditions, Arctic and Antarctic waters could become undersaturated with aragonite, leading to rapid shell corrosion in sensitive marine species like pteropods (Feely et al., 2004, pp. 10-12). Ocean chemistry changes can also alter the behaviour of non-calcifying organisms – for instance, fish predator perception can be impaired in more acidic waters.

Ocean acidification significantly impacts both civilian and military underwater operations. It affects: underwater acoustic wave propagation; sonar performance; durability of materials in ship and submarine construction; communication and navigation systems.

Acidification affects not just open oceans, but also estuaries and coastal zones. Studies on the North Atlantic Subpolar Gyre/NASPG, between 2009 and 2019, show increased anthropogenic carbon absorption and accelerated acidification.

Beyond marine ecosystems, ocean acidification significantly impacts both civilian and military underwater operations. It affects:

- underwater acoustic wave propagation;
- sonar performance;
- durability of materials in ship and submarine construction;
- communication and navigation systems (Theocharidis et al., 2025, pp. 1, 17-19).

Underwater communication, detection, and navigation largely rely on acoustic wave propagation. Acidification alters seawater's acoustic properties, especially by reducing sound absorption. Recent studies show that lower pH decreases acoustic absorption at low frequencies (below 10 kHz) (Hester et al., 2008), allowing such sounds to travel farther. It has dual implications: on the one hand, advantages for long-

range underwater communication and detection, on the other hand, disadvantages for military stealth, as acoustic signals can be detected from greater distances.

U.S. Department of Energy models indicate a 0.3-unit pH drop can increase sound propagation distance by up to 70% in some regions (Seghal et al., 2010). pH changes reduce low-frequency acoustic attenuation, impacting submarine detection and sonar efficiency.

Active and passive sonar systems are affected by changes in sound attenuation and altered temperature/salinity profiles. As pH drops, passive sonar may detect noises from longer distances. Moreover, the active sonar may benefit from improved impulse transmission but face challenges interpreting echoes due to higher background noise. Chemical changes can also affect the acoustic refraction layer, critical for submarine stealth (Office of Naval Research, 2021).

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Changes in sound propagation affect acoustic signatures, potentially altering how vessel signatures are perceived and complicating camouflage and countermeasures strategies.

For submarine navigation, among other things, the variation in water density, which depends on salinity and temperature. On average latitudes, the increase in air and ocean water temperature influences density, so that in the surface layer, which is variable (depending on the season and specific weather-oceanographic conditions), there will be high and homogeneous temperatures, followed by the cold temperature jump layer, with the maximum intensity at the end of summer, and which disappears with the cooling of the weather and the start of convective mixture in the deeper layers. The temperature jump layer also induces the high-water density jump status, namely the high vertical density increase, in a relatively thin water layer (Boșneagu, 2019). The high-water density salt layer whose density is sufficient to support a motionless submersible is called *"liquid bottom" (figure 3).*

Buoyancy condition on the liquid bottom is:

$$\sigma_t V - D = 0 \qquad (1)$$

where: σ_t is seawater density; V – submersible volume; D – submersible weight.

The maintenance of the submersible on the liquid bottom is done through the ballast water manoeuvre (ballasting – deballasting) and the governing installation. In order to have a liquid bottom, it is necessary that, with increasing immersion, without increasing the weight of the submersible, its buoyancy becomes positive.

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The liquid bottom can be calculated with the relationship:

$$q = (\sigma_{tz} - \sigma_{t0}) - (t_0 - t_z)\beta_t 10^3 - K_z 10^3 \qquad (2)$$

where: q is support capacity of the liquid bottom (kg per ton displacement); $(\sigma_{tz} - \sigma_{t0})$ – density difference at the surface and on the z depth; $(t_0 - t_z)$ – temperature difference at the surface and on the z depth; β – steel thermal contraction of the submarine hull, mean coefficient is (0.000036); K – volumetric compression coefficient of the submarine hull, $K_{medium} = 0.00005$

The first term reflects increased buoyancy from higher water density with depth; the other terms reflect buoyancy loss due to temperature drop and pressure increase.

Ocean acidification can accelerate material degradation in marine environments, thus: steel and alloy corrosion in submarine construction is worsened by lower pH; composites and protective coatings may deteriorate faster, requiring new technologies; fixed structures (e.g., submarine cables, exploration probes, communication stations) face increased risk of premature failure (Xia, 2024; Yang, 2024). Acidification accelerates the corrosion of metal equipment and ship components, increasing the need for maintenance and reducing the life of the infrastructure. This situation requires additional investments in the development of materials resistant to increased acidity, with improved anti-corrosion properties.

Acoustic propagation changes and submarine communications changes in acoustic propagation affect submarine communication systems (for example, communications between submarines or between fixed stations and autonomous underwater vehicles/AUVs).

These systems must adapt to the new conditions: recalibration of operating frequencies; optimization of signals to avoid losses caused by increased background noise; integration of alternative technologies, such as optical or electromagnetic underwater communications for short distances.

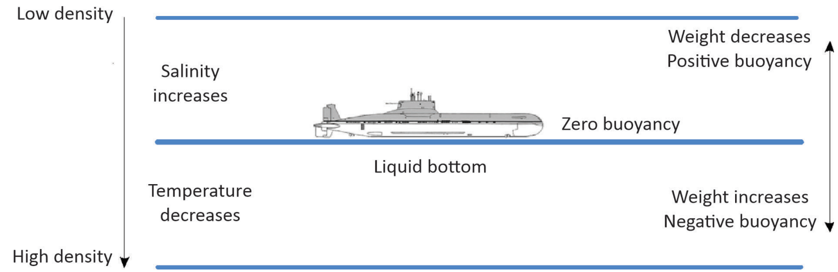

Figure 3: Submarine on the liquid bottom – schematic (author's design)

To address the challenges posed by ocean acidification, the field of submarine operations proposes several adaptive measures as follows:

- development of intelligent sonars capable of interpreting complex acoustic data in variable noise environments;
- use of innovative, corrosion-resistant materials in the design of vessels and underwater equipment;
- adaptation of navigation and detection tactics based on the new acoustic profiles of the oceans;
- promotion of interdisciplinary research for continuous monitoring of acidification and modelling its impact on submarine operations.

In this context, continuous adaptation to the new conditions imposed by chemical changes in the underwater environment is essential. The success of this adaptation depends on: innovation in materials and electronic systems; development of new acoustic propagation models adapted to acidified conditions; strengthening international cooperation in monitoring the impact of acidification on maritime security.

To address the identified challenges, the following *research directions* are suggested:

- advanced modelling of acoustic propagation in acidified oceans to anticipate changes in sonar and communication performance;
- development of new composite materials resistant to corrosion accelerated by marine pH decline;
- optimization of acoustic communication systems by adapting frequencies and coding algorithms to new propagation conditions;
- evaluation of operational risks caused by increased detectability of passive sonar in tactical scenarios;
- continuous monitoring and integration of oceanographic data (pH, temperature, salinity) into submarine mission planning systems.

A longitudinal analysis of ocean acidification indicates a steady increase in the concentration of dissolved CO_2 in seawater, with a progressive decrease in ocean pH over recent decades.

Damage to ecosystems will lead to a decrease in marine biodiversity, which in turn may influence the conduct of military exercises in certain areas for ecological or geopolitical reasons.

A longitudinal analysis of ocean acidification indicates a steady increase in the concentration of dissolved CO_2 in seawater, with a progressive decrease in ocean pH over recent decades. By induction, we can observe that this process influences the physico-chemical characteristics of water, such as sound solubility and galvanic reactions that accelerate material degradation. Inferences from these observations suggest that submarine operations are becoming more exposed to technical and tactical risks: rapid equipment degradation, alteration of passive/active sonar performance, and increased vulnerability to detection.

CONCLUSIONS

Oceanic acidification, driven by increased uptake of carbon dioxide (CO_2) from the atmosphere into seawater, has significant implications for the military field, particularly naval and submarine operations. This change in marine chemistry affects the reliability of sensitive equipment and the performance of acoustic sensors used in submarine

detection. Changes in the propagation of sound through seawater lead to changes in sound attenuation at specific frequencies, which must be exploited for recalibration of sensors, sonar and countermeasures systems.

Affected marine ecosystems can change strategic routes and operations in certain regions. New operational strategies will look at whether marine areas undergoing intense acidification could become either more conducive or vulnerable to submarine operations, requiring constant re-evaluations of noise maps and submarine navigation strategies.

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Acidification negatively affects the efficiency and durability of submarine capabilities. In this context, it is necessary to adapt the design and maintenance strategies for submarine vessels and equipment. It is necessary to develop new corrosion-resistant materials and adapt the sensors to the new chemical conditions of the marine environment. Accelerated corrosion reduces the service life of submarines and autonomous underwater vehicles (AUVs) by requiring investment in acid-resistant alloys or advanced protection systems (e.g., anti-corrosion nanotechnological coatings). Predictive maintenance will need to integrate chemical acidification data into specific algorithms to prevent system failures and reduce maintenance costs.

Potential contributions to the efficiency of military actions under changed chemical conditions of ocean waters could be: the development of an ocean chemical monitoring network dedicated to supporting naval applications; the use of predictive models to adapt the design of new naval equipment; the creation of partnerships between marine research institutes and the defence industry for *dual-use* technological innovation.

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