



A PERSONAL VISION ON THE RESEARCH DIRECTIONS IN MILITARY METEO-OCEANOGRAPHY

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Military meteorology is a fundamental component of applied maritime and military security sciences, integrating marine meteorology and physical oceanography to support decision-making and operative actions in naval theatres. In the context of ongoing climate change, technological progress, and increasing strategic interest in the maritime environment, military weather and oceanography research are experiencing an accelerated and dynamic development.

This paper offers a personal, although scientifically based perspective on the research directions in military oceanography and meteorology, from the point of view of the author's experience in the field, as well as on the implications of these directions on the safety and efficiency of naval operations. The main purpose of the study is to identify and structure relevant research directions in military weather-oceanography, given the current geopolitical context. At the same time, it stresses the need to align national research with NATO trends and standards, as well as the importance of adopting a proactive attitude towards climate change and hybrid threats targeting the Black Sea region.

Keywords: military weather-oceanography; ESA; maritime security; applied research; physical oceanography;

INTRODUCTION

In the context of the complexity of the maritime operational environment, military weather-oceanography/METOC is becoming a component of great strategic importance, and information about the natural environment, especially meteorological and oceanographic ones, is becoming essential in the planning and conduct of military operations. Military meteorology, as a discipline applied at the intersection of science and strategy, plays a fundamental role in ensuring information superiority, in reducing operational risks and in supporting tactical and strategic decision.

With accelerated technological development, the emergence of new autonomous naval platforms, as well as the increasing complexity of modern naval operations, the need for advanced research in the field of military meteorological oceanography is more pressing than ever. Romania, as a NATO member state with access to a strategic interest area – Black Sea –, has the obligation to strengthen its scientific and operational capabilities in this field.

The world ocean, covering approximately 71% of the Earth's surface, is not only a natural reservoir of resources but also a strategic operational environment (The Intergovernmental Oceanographic Commission of UNESCO/IOCUNESCO, 2021). With an estimated volume of 1.35 billion km³ and an average depth of around 3,700 meters, it contains 97% of Earth's water but remains largely unexplored: less than 20% of the ocean floor has been accurately mapped (Wölfel et al., 2019).

In this context, military meteo-oceanography – a specialized component of military science – has become increasingly important. It provides integrated assessments and forecasts of the atmosphere-ocean environment, with direct applications in navigation safety, weapon system efficiency, and naval platform survivability (Naval Oceanographic Office/NAVOCEANO, 2020).

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Military marine meteorology analyses the influence of atmospheric factors on equipment and crew performance, while military oceanography provides essential information on hydro-physical processes for planning and conducting naval operations (Boșneagu, 2014).

This paper aims to provide a personal view on the main research directions that can contribute to the consolidation and optimization of military capabilities in maritime areas of interest, in the context of the future evolution of military weather-oceanography. The presentation, made both from the perspective of the national environment and within NATO structures, is based on an in-depth documentary analysis, complemented by a strategic and exploratory approach. Within this framework, potential areas of development with direct applicability in support of naval, air and ground forces are highlighted.

The main purpose of the paper is to identify and structure relevant research directions in military weather-oceanography, starting from the current geopolitical context, technological developments and maritime security needs, from a personal but scientifically-based perspective. The objectives of the research are: the analysis of current trends in international and military meteorological research; the identification of areas of strategic interest for military research applied in the maritime environment; the examination of the contribution of meteorology and oceanography to the success of naval and air operations; the proposal of future research directions, relevant to the Romanian and NATO context.

After the presentation of the research methodology, a synthesis of the current trends in the field will be made, followed by the identification of the relevant research directions and a SWOT analysis of the field. Finally, the conclusions and suggestions are formulated regarding the consolidation of scientific and operational capacity in military weather-oceanography.

METHODOLOGY

This article proposes a structured personal vision of a niche domain, with a focus on integrating environmental factors into the planning and execution of military operations. It offers a framework for reflection and potential research directions for future researchers, planners, or decision-makers in the military field.

This is a qualitative, exploratory, and prospective study, aimed at formulating a reasoned personal vision of strategic and scientific development directions in military meteo-oceanography. It also includes elements of documentary and comparative analysis, as well as extrapolations based on current trends and possible future operational needs.

Research methods and techniques used:

- a) document analysis: scientific studies and journal articles on military meteorology and oceanography; public NATO and national military documents; research centre reports (e.g., US Naval Research Laboratory, NATO CMRE);
- b) comparative analysis: comparing NATO-level research directions; identifying differences between civilian and military approaches in meteo-oceanography;
- c) interviews and informal consultations with military specialists, meteorological officers, or oceanographers to validate hypotheses or perspectives.

The theoretical foundation integrates concepts from applied meteorology, physical oceanography, maritime geostrategy, and military intelligence. It also highlights the interdependencies between the operational environment and meteo-oceanographic information in modern theatres of operation.

The limitations of this research include: limited access to sensitive information on concrete applications of high-end military meteo-oceanographic research; high uncertainty regarding long-term technological projections.

CURRENT INTERNATIONAL RESEARCH DIRECTIONS IN METEO-OCEANOGRAPHY

The study of physical oceanography and marine meteorology as well as of the atmosphere-ocean interaction is crucial for understanding the global climate system, sustainably harnessing marine resources, and developing naval technologies.

Current international research directions in these fields include:

- the role of the ocean in climate evolution: oceans absorb about 90% of the excess heat caused by the greenhouse effect, acting as climate regulators (Intergovernmental Panel on Climate



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- Change/IPCC, 2021); through thermohaline¹ circulation, heat is redistributed, influencing global climate dynamics;
- exploitation of marine resources: oceans provide significant sources of food, energy, and raw materials; research focuses on the sustainable exploitation of these resources, including offshore deposits and biological resources (Food and Agriculture Organization/FAO, 2022);
- marine biodiversity conservation: over 230,000 marine species are identified, but it is estimated that over two million exist (Costello et al., 2010); protecting them involves habitat mapping and anthropogenic pressures monitoring;
- weather and extreme phenomena forecasting: the *El Niño–Southern Oscillation (ENSO)* has a major impact on global climate; understanding it requires the integration of oceanographic and meteorological data (McPhaden et al., 2006);
- maritime transport and economy: oceanography is essential for maritime navigation, as currents, tides, and waves influence trade routes and port operations (International Maritime organization/IMO, 2020) (figure 1).

Modern meteo-oceanographic research relies on advanced technologies that allow for the collection of complex data (Boșneagu, 2019):

- oceanographic satellites*: monitor sea surface temperature, ocean levels, and biological productivity in real time (European Space Agency/ESA, 2023);
- autonomous vehicles (Autonomous Underwater Vehicle/AUVs and Remotely Operated Vehicle/ROVs)*: provide access to hard-to-reach areas, allowing sample collection and direct measurements (Yoerger et al., 2007);
- Argo network*: over 3,800 active floats measuring temperature and salinity up to 2,000 m depth (Roemmich et al., 2019);

¹ Worldwide system of deep ocean currents driven by differences in temperature (thermo-) and salinity (haline) of seawater. These differences influence the density of water, which determines its vertical and horizontal movements throughout the entire global ocean (Copernicus – Glossary, <https://marine.copernicus.eu/ro/explainers/glossary>), A.N.

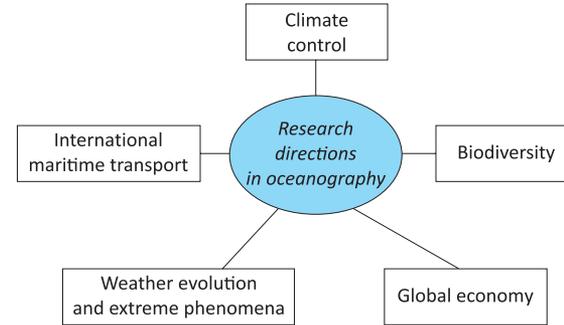


Figure 1: Current Research Directions in Meteo-Oceanography (Ib., author's adaptation)

- CTD and SVP equipment (Conductivity, Temperature and Depth/CTD and Sound Velocity Profilers/SVP)*: accurately characterize the water column by conductivity, temperature, and pressure;
- Doppler current meters and sound profilers*: Essential for analysing acoustic propagation and local ocean circulation (figure 2).

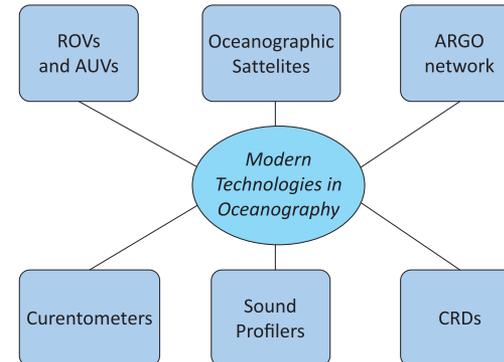


Figure 2: Modern Technologies Used in Meteo-Oceanography (Ib.)



Ocean exploration remains incomplete, limited by the technical difficulties and resources needed to study the entire ocean system. Climate change has a significant impact on the ocean environment, manifesting itself in phenomena such as water acidification, rising ocean temperatures and deoxygenation of certain marine areas.

Although oceanography research has made significant progress in recent decades, this science still faces numerous major challenges affecting full understanding of the ocean environment. First, *ocean exploration* remains incomplete, limited by the technical difficulties and resources needed to study the entire ocean system. Secondly, *climate change* has a significant impact on the ocean environment, manifesting itself in phenomena such as water acidification, rising ocean temperatures and deoxygenation of certain marine areas (Bindoff et al., 2019). These changes not only affect biodiversity and the functioning of marine ecosystems, but also jeopardise ocean-dependent human resources and activities, such as fishing and maritime transport. Last but not least, marine pollution, especially microplastics and industrial pollutants, threatens the balance of marine ecosystems (The United Nations Environment Programme/UNEP, 2021).

In this context, further research and the development of advanced technologies are essential to be able to sustainably monitor and manage the ocean environment in the face of these global challenges.

NEW RESEARCH DIRECTIONS IN MILITARY METEO-OCEANOGRAPHY ACCORDING TO NATO DOCTRINE

Effective planning of naval operations requires evaluating the three-dimensional operational environment, which includes air, surface, and underwater components. This integrated approach allows the command to obtain a complete and accurate picture of the conditions on the ground, facilitating quick and well-grounded decisions in the complex context of the marine environment.

Contemporary military meteorological and oceanographic research focuses on several strategic directions, aimed at optimizing operational capabilities. These include integrating weather-oceanographic data into command-and-control systems (Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance/C4ISR) to ensure an up-to-date and consistent situation during missions. The focus is also on the development of advanced predictive models to provide accurate estimates of acoustic propagation, sea state and marine currents, which are essential for the success of underwater operations. The in-depth study of the influence

of the seabed on acoustic detectability and sonar performance is a critical component, as substrate conditions can significantly affect the results of reconnaissance and surveillance missions. In addition, it aims to increase the resilience of naval forces in severe weather-oceanographic conditions, to preserve the efficiency and safety of operations in the most difficult situations.

It is important to stress that superiority in the naval battlefield depends largely on a deep understanding of the environment. Detailed knowledge of the physico-chemical and dynamic characteristics of the ocean provides a decisive strategic advantage, allowing naval forces to anticipate and respond effectively to the various challenges of the maritime environment (NATO Science and Technology Organization/NATO STO, 2017).

RESULTS AND DISCUSSION

Progress made over the past two decades in military meteo-oceanography has led to more effective integration of atmospheric and oceanic data into naval operation planning. The introduction of modern observation systems – such as the global ARGO buoy network, AUVs, and meteo-oceanographic satellites – has improved the accuracy of sea and weather forecasts in hostile or geophysically complex environments (Wunsch, 2006; Schiller & Brassington, 2011). In the current context, technological modernisation of global and regional marine and submarine research networks is considered to be a strategic priority for the benefit of national defence and security. At the same time, it is essential that environmental monitoring and data collection programmes continue, ensuring truly global coverage and providing vital information for naval operations, there by contributing to streamlining and securing maritime missions.

A notable result is the significant reduction of uncertainty in mission planning, especially in conflict areas where salinity, temperature, and current data influence acoustic detection, submarine navigation, and naval weapon efficiency (Curtin et al., 1993; Dombrowsky, 2007). The combined use of meteorological and oceanographic data has optimized transit routes, minimized exposure to unfavourable oceanic conditions, and improved evasion capabilities (NATO RTO-TR-AVT-181, 2010). Identifying and implementing innovative solutions



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for the rapid and efficient interpretation of relevant meteorological and oceanographic data is a fundamental necessity in the field of maritime research. In this context, the use of advanced technologies, such as artificial intelligence, becomes imperative to optimize the process of analysis and decision-making. It also requires the training and recruitment of double-skilled personnel, both from a scientific perspective and in the operational area of command, to ensure effective interoperability and accurate interpretation of data in critical time conditions.

Tactical meteo-oceanography directly enhances naval simulation performance by providing a 3D projection of the operational field (Cummings et al., 2009). For example, sound propagation models adjusted by temperature, salinity and pressure allow better calibration of sonar detection systems.

I appreciate that the professional experience gained provides me with the necessary framework to formulate perspectives and orientations regarding future research directions in military meteorological oceanography. Here are some examples:

1. Daily and mission-specific hydrolocation forecasting is a complex issue that needs real, validated, and easily interpretable data for naval operations. It requires processing software and equipment, real-time data collection tools, and, most importantly, qualified personnel.

2. Despite advancements, limitations remain in the spatial and temporal coverage of data, especially in polar regions and deep-sea areas that are poorly explored. The need for real-time integration of data from various sources (space, maritime, atmospheric) presents methodological, technological, and information security challenges. For example, the “Sea Shield” exercise, periodically conducted in the Black Sea, provides a relevant example of the integrated application of military meteorology and oceanography in an environment with complex hydro-meteorological characteristics. A decision support system was implemented during this exercise, based on real-time data from mobile platforms (ROVs, UAVs) and automated weather stations deployed near the operational area. However, there is still significant need for investment in decision-making tools, equipment, funding, and human resources.

3. The use of oceanographic data – particularly thermohaline stratification parameters – enabled the optimization of sonar sensor positioning for the detection of underwater threats. At the same time, high-resolution meteorological information supported naval-air planning, offering accurate forecasts on the cloud cover and atmospheric turbulence that influenced aerial operations. Nonetheless, given the volatility and variability of real data from the marine and submarine environment, we believe that there is still a significant need for development in the field of research, equipment, operationalisation and quantification of these data for military purposes.

4. All these efforts led to improved efficiency in detecting underwater objects, mainly attributed to the integration of meteorological and oceanographic information. Moreover, there was a reduction in the reaction time of forces during active tactical phases, demonstrating the added value of this informational component within the mission’s decision-making architecture.

5. Automation and artificial intelligence in meteorological and oceanographic forecasting: using AI algorithms for high-precision forecasts; integration with C4ISR systems; developing machine learning-based algorithms capable of real-time interpretation of data from satellites, weather radars, and in-situ oceanographic sensors; using neural networks to improve wave, current, and severe atmospheric event forecasting in tactical environments; integrating these systems into C4ISR platforms to directly support military command structures.

6. Use of autonomous observation systems (UAV/USV/SATCOM): oceanographic or weather sensors adapted for marine or aerial environments, integrated into military networks; implementing a network of autonomous maritime platforms, oceanographic gliders, and aerial drones capable of monitoring meteo-oceanographic parameters in strategically important areas (e.g., offshore platforms, military navigation corridors); adapting commercial technologies for military use: sensors for temperature, salinity, pressure, ocean currents, and atmospheric turbulence; equipping them with encrypted communication capabilities for integration into combat networks.



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7. Development of advanced marine environment simulation models: using supercomputers for 3D modelling, correlated with simulated military manoeuvres (wargaming).

8. Use of tactical meteo-oceanography for special operations: localized micro-forecasts for divers, underwater drones, SEAL operations; applied research on the local effects of waves, tides, and winds on special forces insertion operations; miniaturization of portable sensors for advanced reconnaissance forces; development of mobile applications with real-time meteo-oceanographic support for field operators.

9. Adaptation to climate change and hybrid risks: impact of sea level rise, extreme waves; meteo-oceanography as a tool for conflict prevention/anticipation in hybrid scenarios: analysis of climate change impacts on maritime theatres (intensified storms, shifting currents, shorter calm periods); research on using meteo-oceanographic data to anticipate hybrid actions in the maritime domain (illegal migration, energy sabotage, civil-military interference); integration of historical and climatological data in long-term risk assessments.

10. SWOT analysis applied to military meteo-oceanographic research in Romania is presented in *table 1*.

Table 1: SWOT analysis applied to military meteo-oceanographic research in Romania (author's design)

Strengths	Weaknesses	Opportunities	Threats
Integration of meteo-oceanography in NATO doctrine and existence of common standards	Limited infrastructure for high-precision oceanographic observations in Romania	Development of autonomous platforms (USV, UAV, oceanographic gliders)	Risk of compromised communications and meteo-oceanic data
Access to satellite data, numerical models, and international platforms	Dependence on external partners for many advanced capabilities	Integration of AI and Big Data into operational environment modelling	Poor exploitation or misinterpretation of data in critical conditions



Strengths	Weaknesses	Opportunities	Threats
Possibility of collaboration with research institutes and technical universities	Underfunding of applied military research in the maritime operational environment	Growing NATO interest in the Black Sea region	Political instability may affect project continuity and funding
Existence of military and civilian personnel specialized in operational meteorology and oceanography	Lack of an autonomous network of meteo-oceanographic sensors in the Black Sea	Participation in European research projects and international know-how exchanges	Lack of a coherent national strategy for military-applied meteo-oceanography
Expertise accumulated in NATO	Limited funding	Emerging technologies	Electronic warfare, sabotage
Available satellite data	Outdated meteorological infrastructure	International partnerships	Human resource overuse

11. Development of Romania's national autonomous meteo-oceanographic observation network in the Black Sea.

12. Development of a *Meteo-Oceanographic Centre of Excellence* in Romania, in cooperation with NATO partners and civilian institutions.

13. Attracting European funds for applied research in the maritime security environment.

CONCLUSIONS

Investments in military weather-oceanographic research should be perceived as a strategic necessity, rather than as a simple option. They provide the armed forces with an essential information advantage and contribute to ensuring maritime security, optimising operational performance and strengthening national resilience in the face of emerging challenges in the maritime environment.



Military meteo-oceanography represents an increasingly important strategic domain in the context of modern operations conducted in maritime and coastal environments. The complexity of theatres of operation, the rapid response required of command structures, and the risks posed by natural phenomena necessitate constant adaptation of observation, analysis, and forecasting capabilities.

In addition, military meteo-oceanography is clearly emerging as a critical field in the 21st century naval security architecture. Investments in research, technology, and the operational integration of environmental data must continue in order to support information superiority and strategic efficiency of naval forces. International cooperation in exploring and protecting the marine environment is essential both for peace and defence.

Military meteo-oceanography plays a fundamental strategic role in the preparation, planning, and execution of modern naval operations. Recent technological developments – including oceanographic satellites, CTD sensors, autonomous underwater vehicles, and numerical modelling systems – have transformed how naval forces perceive and utilize the marine environment.

The integration of atmospheric and oceanographic data into a unified analysis framework directly contributes to optimizing tactical and operational decisions, especially in maritime theatres with complex hydrometeorological dynamics. The analysis of the “Sea Shield” exercise demonstrates the immediate operational relevance of military oceanography, highlighting its impact on detection, force mobility, and mission safety.

Despite these advances, challenges remain regarding real-time data accessibility, system interoperability, and forecast accuracy in poorly instrumented or extreme oceanic environments. Therefore, future research should focus on developing adaptive prediction models, integrating artificial intelligence into METOC analysis, and expanding autonomous data collection capabilities in ocean depths.

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This research provided a personal insight into future research directions in the field of military weather-oceanography, highlighting the importance of integrating emerging technologies such as artificial intelligence, autonomous systems, advanced numerical models and dedicated applications for special operations. It also stressed the need to align national research with NATO trends and standards, as well as to adopt a proactive approach to climate change and hybrid threats in the Black Sea region.

The SWOT analysis revealed a significant development potential, despite structural and institutional limitations, thus highlighting the importance of strengthening the collaboration between the military environment, the academic environment and the research and development sector, as well as the need to attract international funds to initiate applicative projects.

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